Jet quenching and medium response

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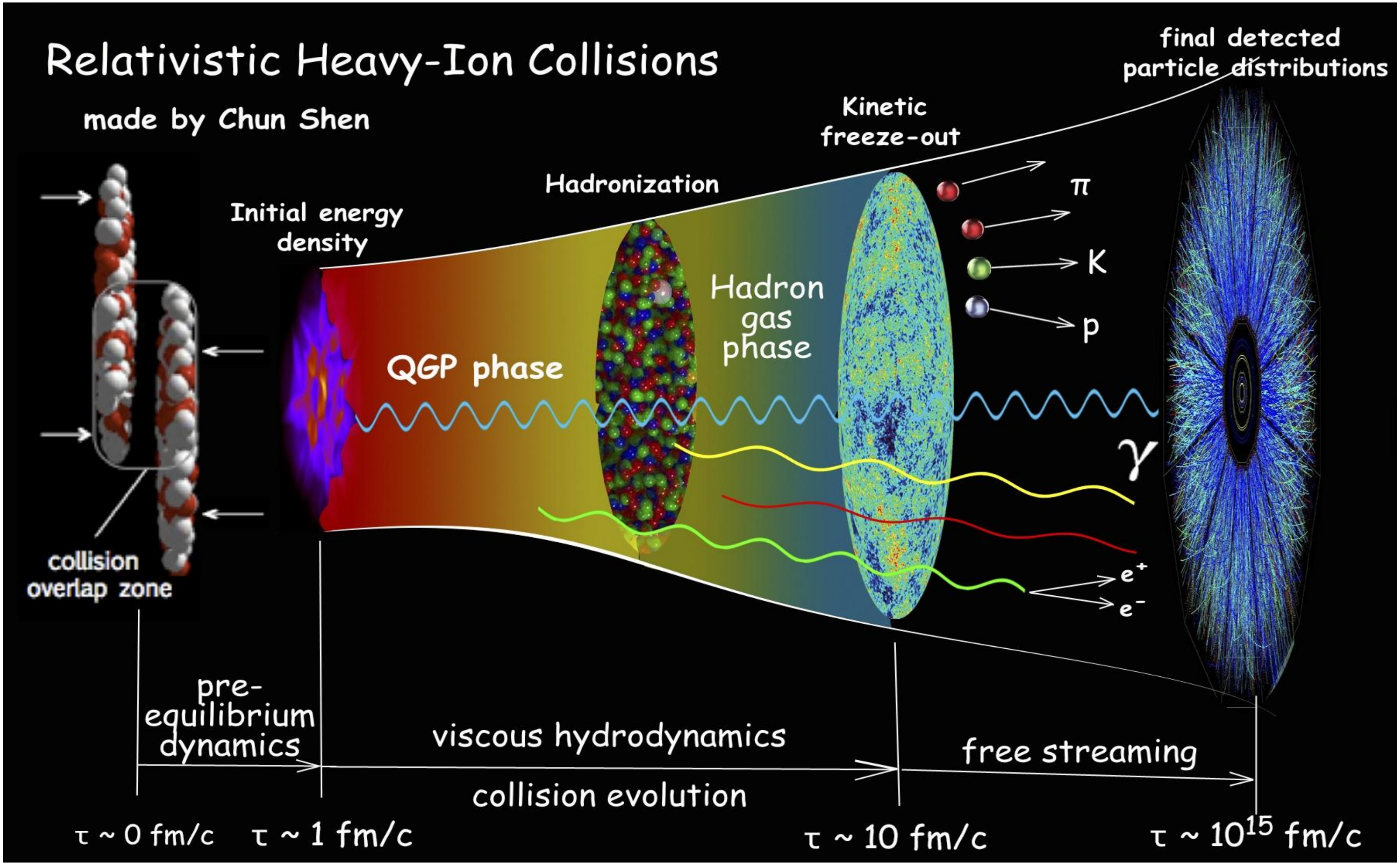
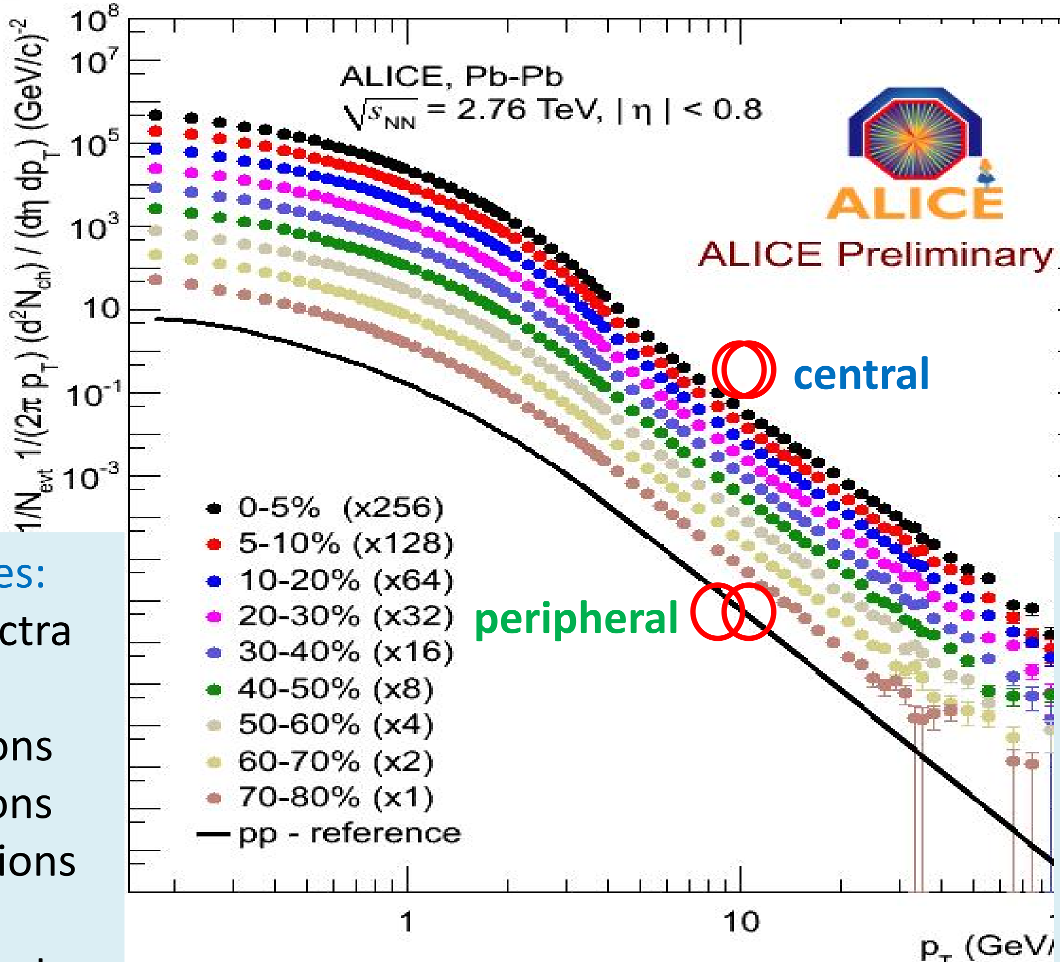
Outline

- Introduction
- Jet qenching
  - High p_T hadrons, flavor hierarchy of jet quenching
- Medium response
  - Full jets, jet-hadron correlations
- Summary

“Standard Model” of RHIC & LHC heavy-ion collisions



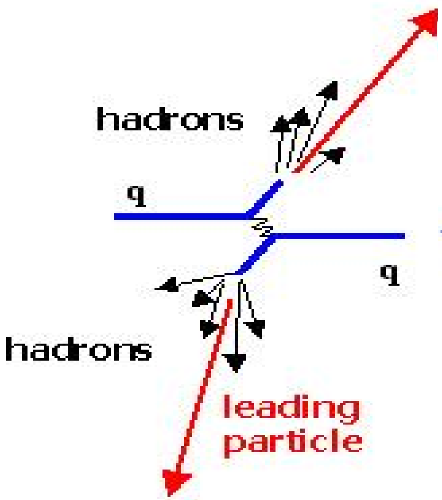
Probes of QGP in heavy-ion collisions

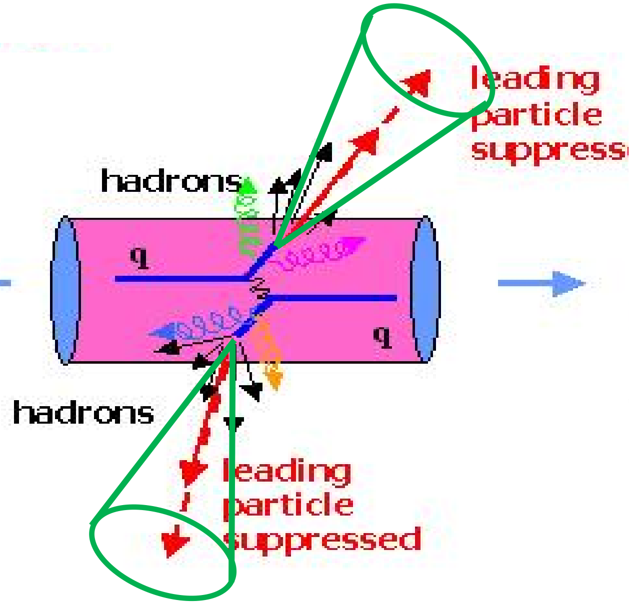


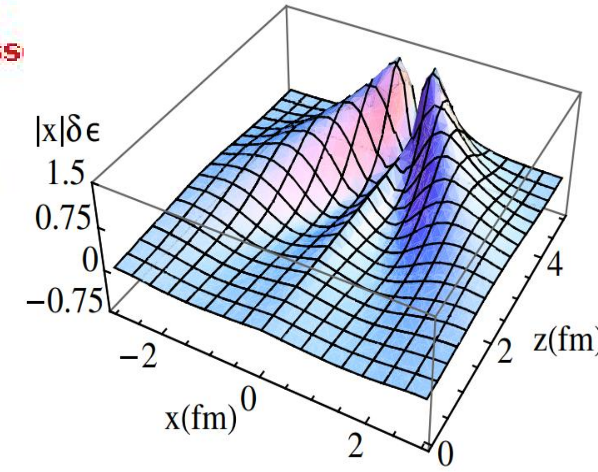
Soft Probes:
Yields/Spectra
Flows
Fluctuations
Correlations
Decorrelations
…
“Internal” probes

Hard Probes:
Large p_T hadrons
Jets
Heavy quark/hadrons
Quarkonia
EM probes
…
“External” probes

Jet quenching





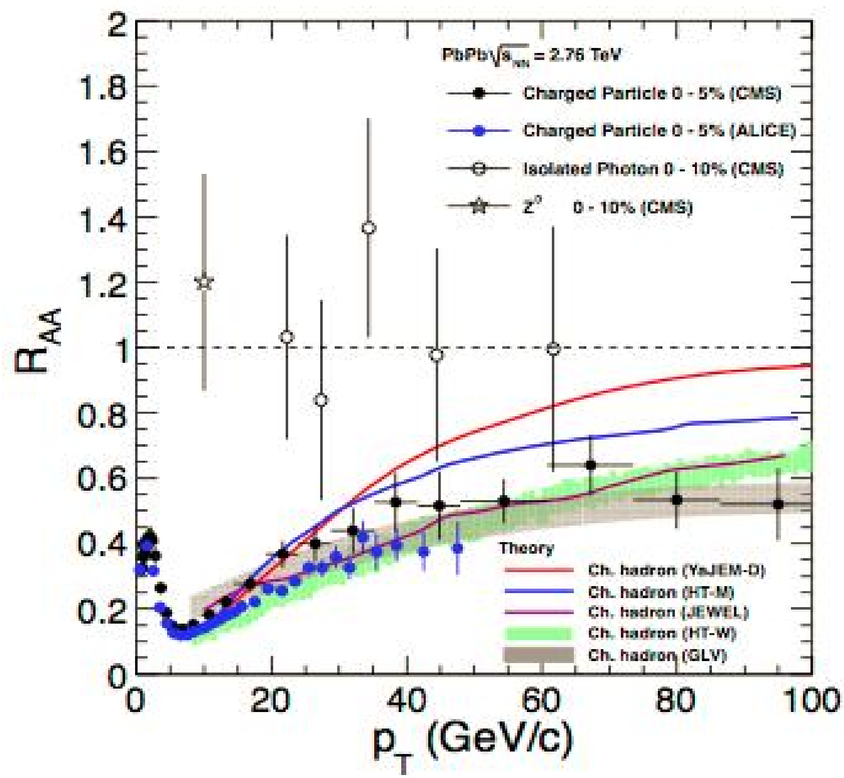


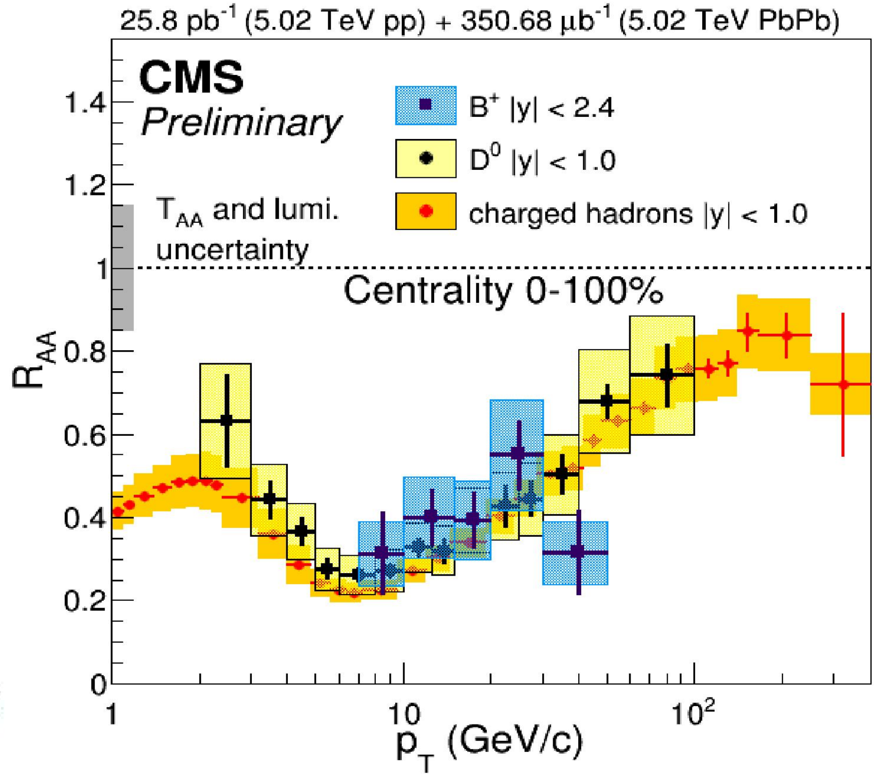
N+N

A+A: jet quenching

(1) jet energy loss (2) jet deflection and broadening (3) modification of jet structure
(4) jet-induced medium excitation (medium response)

Nuclear modifications of high p_T hadrons





$$R_{AA} = \frac{1}{N_{coll}} \frac{dN^{AA} / d^2 p_T dy}{dN^{pp} / d^2 p_T dy}$$

Flavor hierarchy of parton energy loss:
$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$.
However, $R_{AA}(h) \approx R_{AA}(D)$. Why?

Linear Boltzmann Transport (LBT) Model

- **Boltzmann equation:** $$p_1 \cdot \partial f_1(x_1, p_1) = E_1 C[f_1]$$
- **Elastic collisions:**

$$\Gamma_{12\to 34} = \frac{\gamma_2}{2E_1} \int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \int \frac{d^3p_4}{(2\pi)^3 2E_4} \times f_2(\vec{p}_2) \left[1 \pm f_3(\vec{p}_1 - \vec{k})\right] \left[1 \pm f_4(\vec{p}_2 + \vec{k})\right] \times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4) |\mathcal{M}_{12\to 34}|^2$$

$$P_{el} = 1 - e^{-\Gamma_{el} \Delta t}$$

Matrix elements taken from LO pQCD

- **Inelastic collisions:**

$$\langle N_g \rangle = \Gamma_g \Delta t = \Delta t \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$

$$P_{inel} = 1 - e^{-\langle N_g \rangle}$$

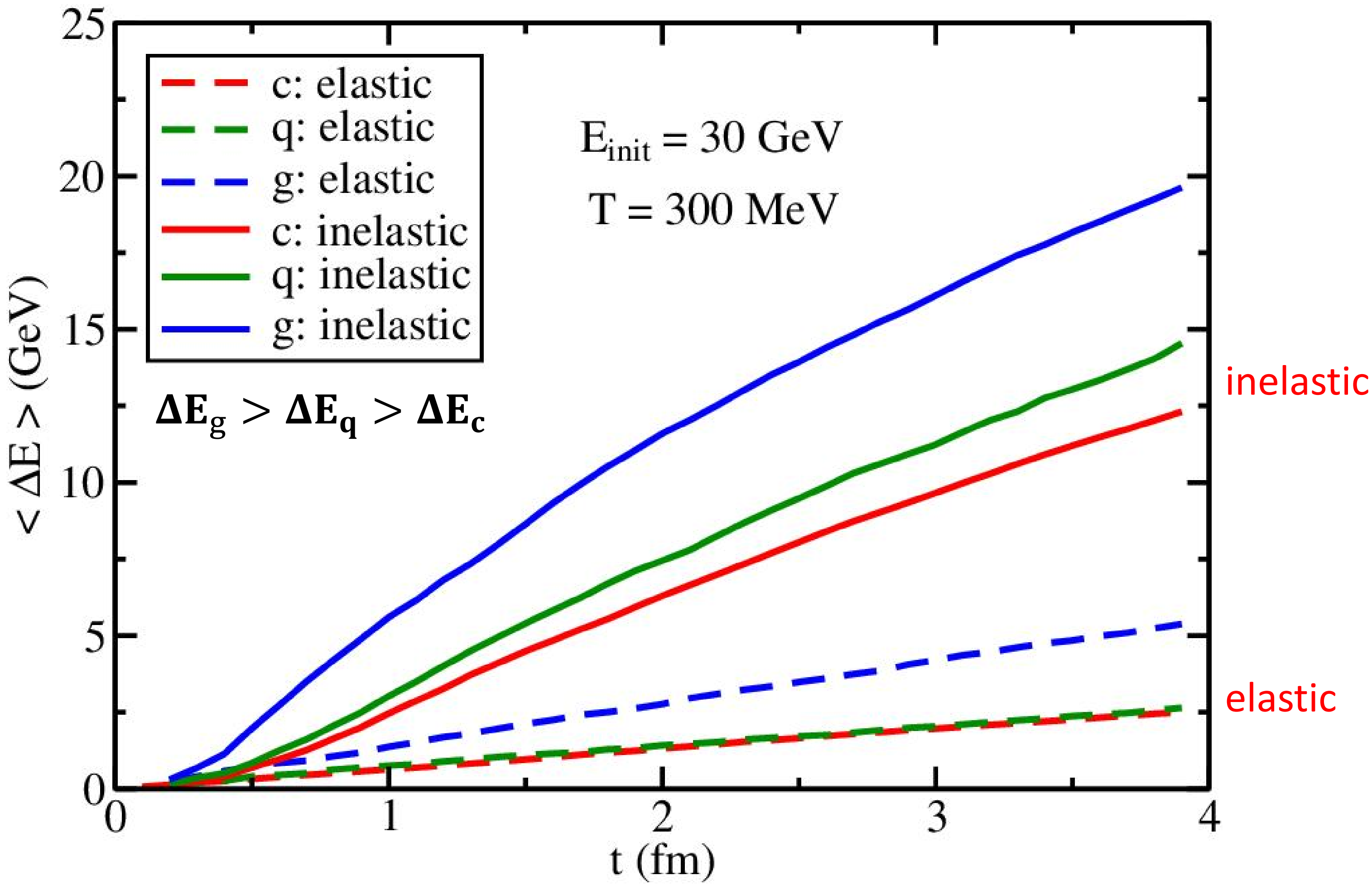
Medium-induced radiation spectra taken from HT: Guo, Wang PRL 2000; Zhang, Wang, Wang, PRL 2004; Majumder, PRD 2012, Zhang, Hou, GYQ, PRC 2019; Zhang, GYQ, Wang, PRD 2019.

- **Elastic + Inelastic:**

$$P_{tot} = 1 - e^{-\Gamma_{tot} \Delta t} = P_{el} + P_{inel} - P_{el} P_{inel}$$

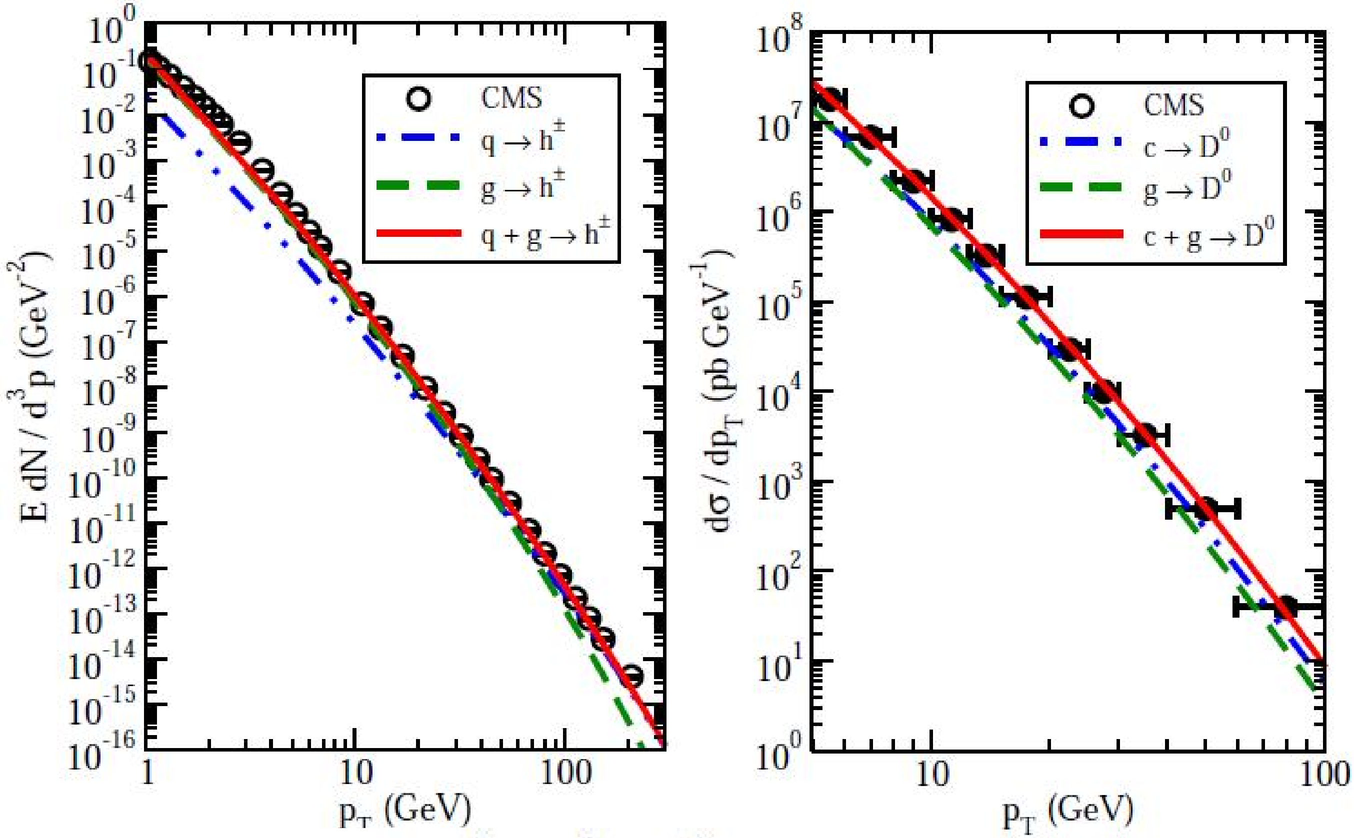
He, Luo, Wang, Zhu, PRC 2015; Cao, Luo, GYQ, Wang, PRC 2016, PLB 2018; etc.

Flavor hierachy of parton energy loss



He, Luo, Wang, Zhu, PRC 2015; Cao, Luo, GYQ, Wang, PRC 2016 ; PLB 2018; etc.

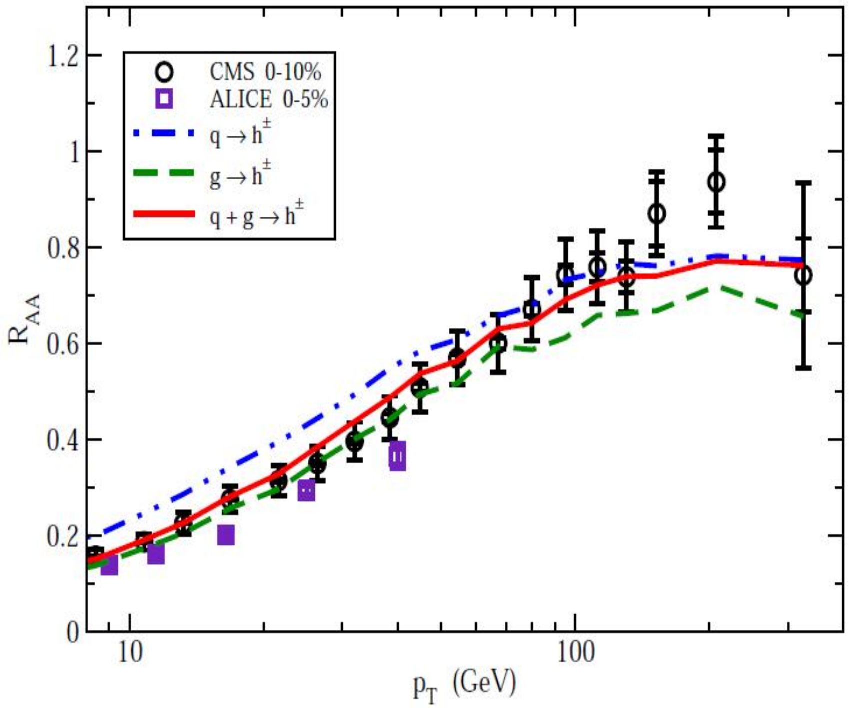
Hadron productions in pp collisions @ NLO

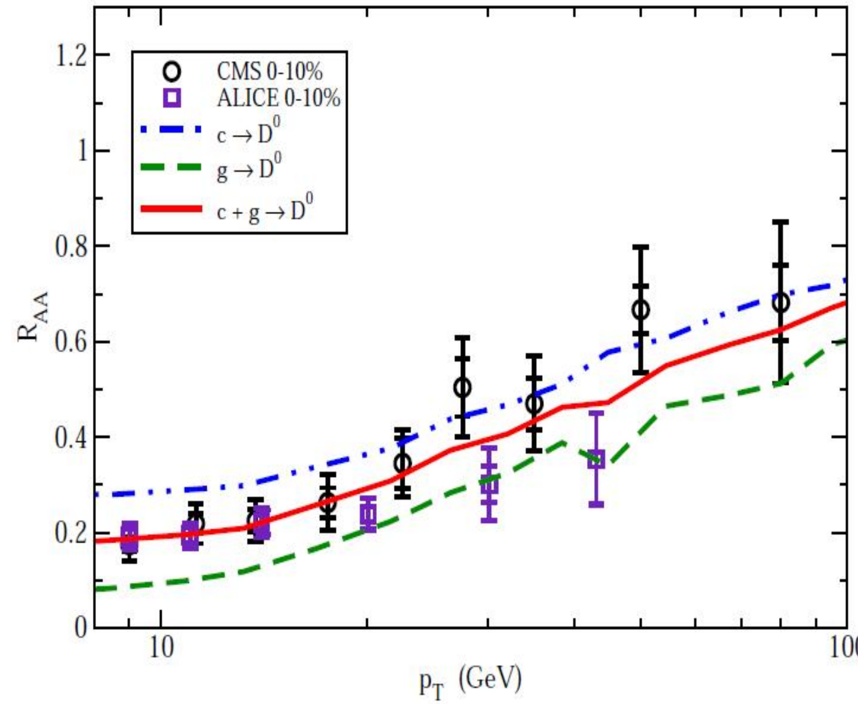


$$d\sigma_{pp\to hX} = \sum_{abc} \int dx_a \int dx_b \int dz_c f_a(x_a) f_b(x_b)\, d\hat{\sigma}_{ab\to c} D_{h/c}(z_c)$$

Based on B. Jager, A. Schafer, M. Stratmann, and W. Vogelsang, Phys. Rev. D67, 054005 (2003)
F. Aversa, P. Chiappetta, M. Greco, and J. P. Guillet, Nucl. Phys. B327, 105 (1989).

Flavor hierarchy of jet quenching

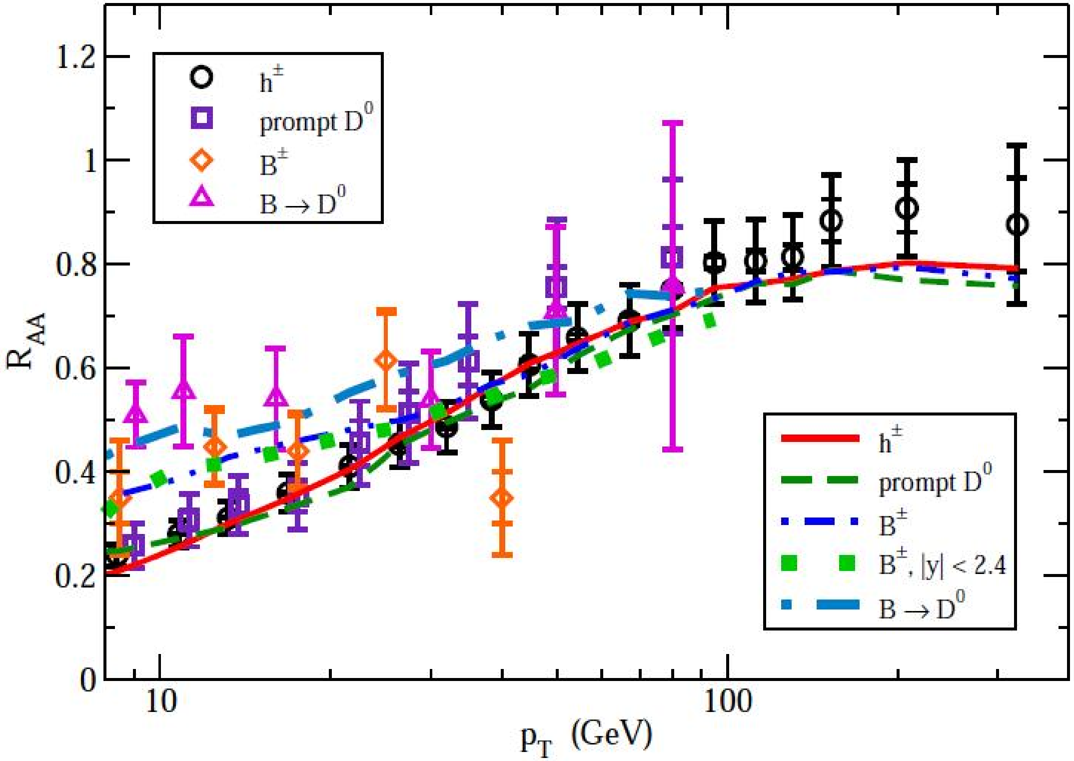




A state-of-art jet quenching framework (NLO-pQCD + LBT + Hydrodynamics)
Quark-initiated hadrons have less quenching effects than gluon-initiated hadrons.
Combining both quark and gluon contributions, we obtain a nice description of charged hadron & D meson R_{AA} over a wide range of p_T.

Xing, Cao, GYQ, Xing, PLB 2020

Flavor hierarchy of jet quenching

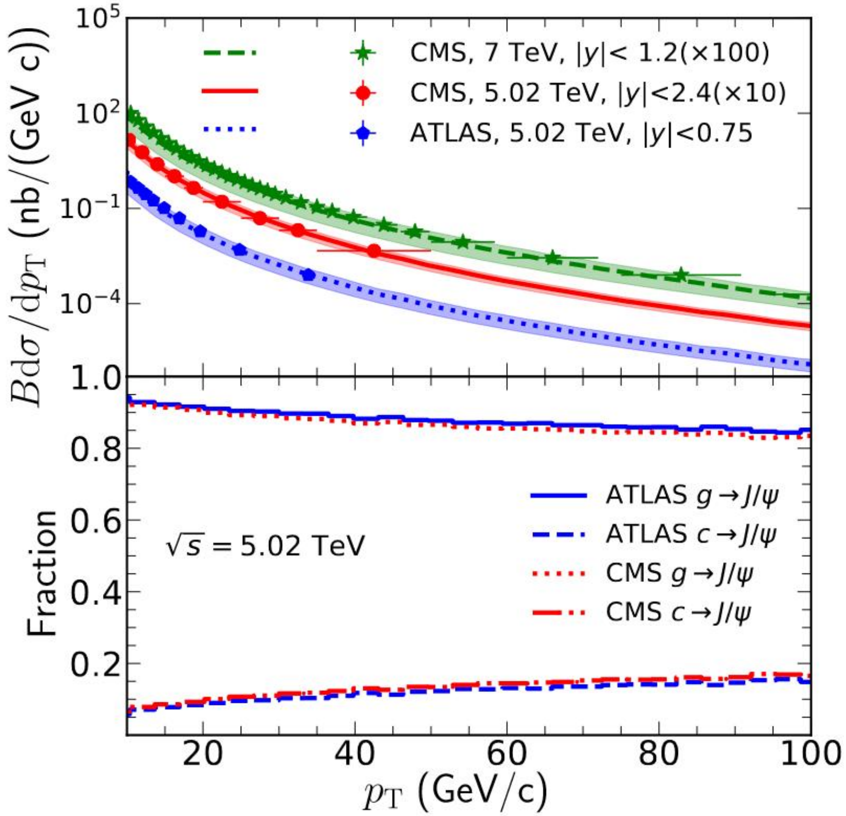


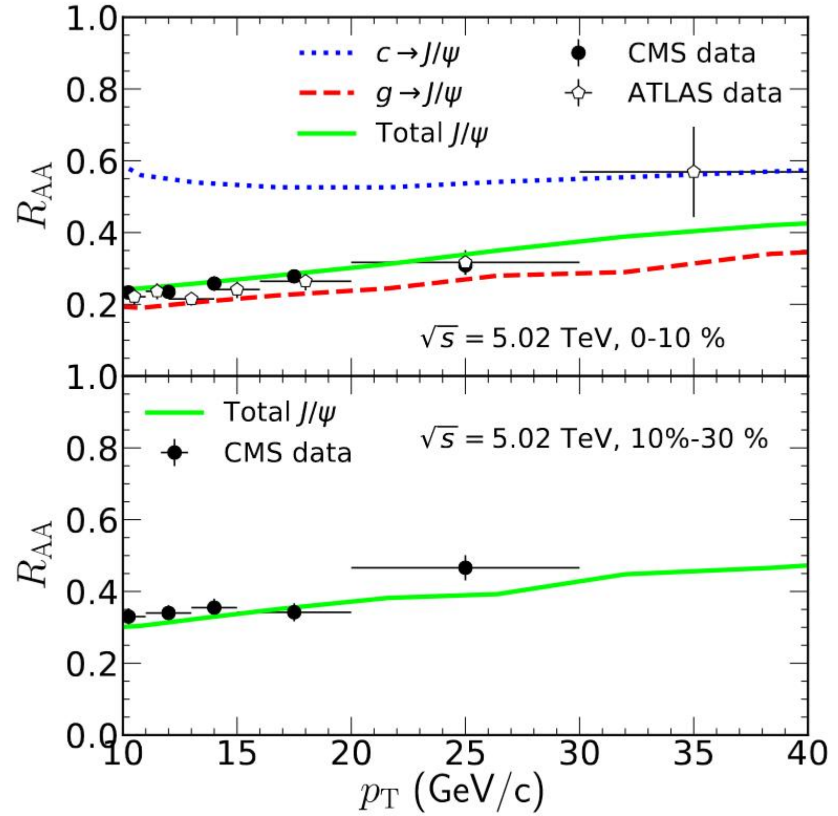
A state-of-art jet quenching framework (NLO-pQCD + LBT + Hydrodynamics)

At $p_T > 30$-40 GeV, B mesons will also exhibit similar suppression effects to charged hadrons and D mesons, which can be tested by future measurements.

Xing, Cao, GYQ, Xing, PLB 2020

Gluons dominate high p_T J/Ψ suppression





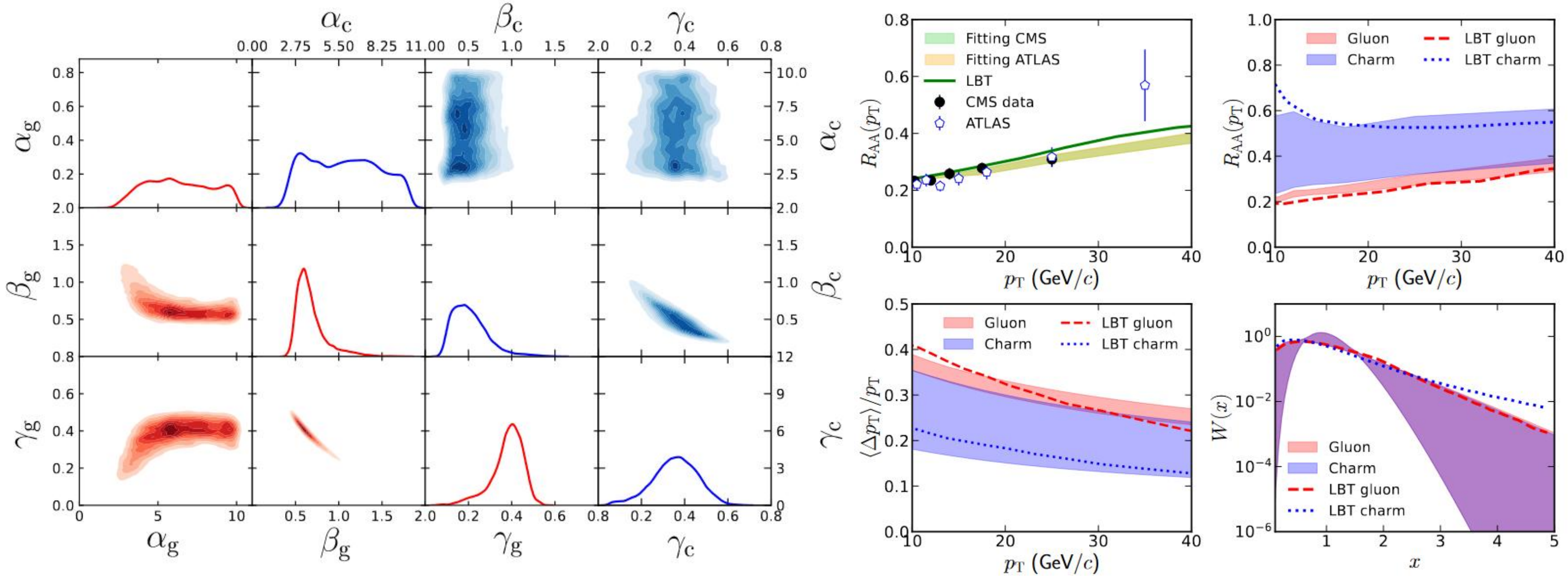
$$d\sigma[AB \to J/\psi + X] = \sum_i d\hat{\sigma}_{AB\to i+X} \otimes D_{i\to J/\psi} \qquad D_{i\to J/\psi}(z,\mu) = \sum_n \hat{d}_{i\to[Q\bar{Q}(n)]}(z,\mu)\langle \mathcal{O}^{J/\psi}_{[Q\bar{Q}(n)]}\rangle$$

The gluon jet quenching is the driving force for high p_T J/Ψ suppression.

S.-L. Zhang, J. Liao, GYQ, E. Wang, H. Xing, 2208.08323, Sci.Bull. 2023, in press.

Ma, Qiu, Zhang, PRD, 2014; Bodwin, Kim, Lee, JHEP 2012; Bodwin, Chung, Kim, Lee, PRL 2014

Extracting gluon energy loss distribution



$$\frac{d\sigma^{AA}}{dp_T} = \sum_i \int \frac{d\Delta p_T^i}{\langle \Delta p_T^i \rangle} \frac{d\sigma^{pp}(p_T + \Delta p_T^i)}{dp_T} W^i(x) \otimes D_{i \to J/\psi}$$

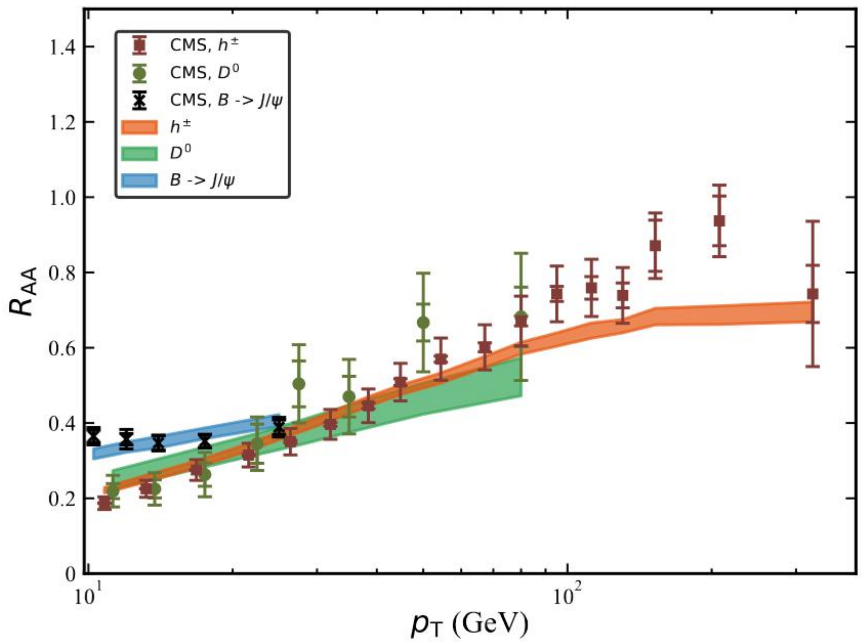
$$\langle \Delta p_T^i \rangle = \beta_i p_T^{\gamma_i} \log(p_T)$$

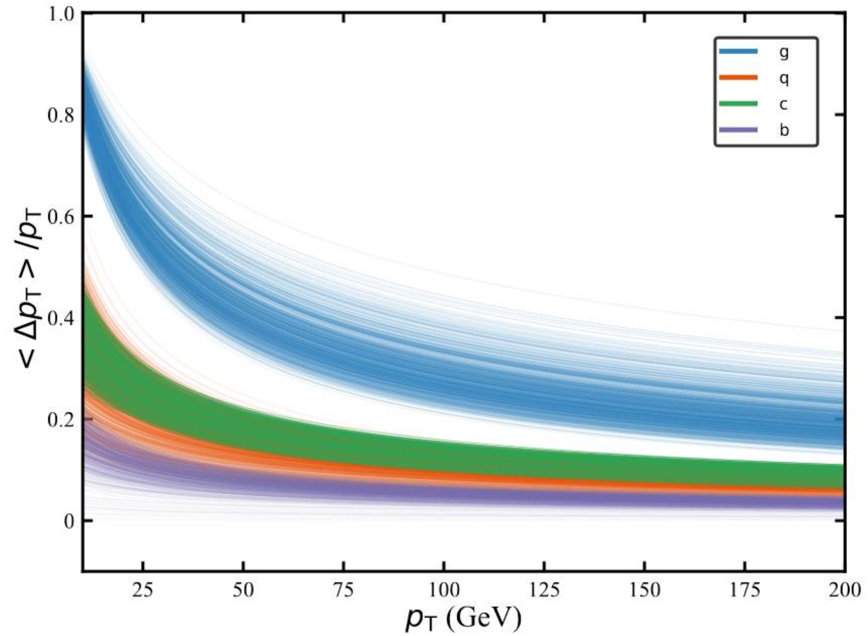
$$W^i(x) = \frac{\alpha_i^{\alpha_i} x^{\alpha_i - 1} e^{-\alpha_i x}}{\Gamma(\alpha_i)}$$

The first quantitative extraction of gluon energy loss distribution in QGP.
Probe the flavor dependence of jet quenching!

S.-L. Zhang, J. Liao, GYQ, E. Wang, H. Xing, 2208.08323, Sci.Bull. 2023, in press.

Flavor hierarchy of parton energy loss





$$\frac{1}{\langle N_{\rm coll}\rangle}\frac{d\sigma_{\rm AA\to hX}}{dp_{\rm T}^h} = \sum_j \int dp_{\rm T}^j dx dz \frac{d\hat{\sigma}_{\rm p'p'\to jX}}{dp_{\rm T}^j}(p_{\rm T}^j)\; W_{\rm AA}(x) D_{j\to h}(z)\delta\left(p_{\rm T}^h - z(p_{\rm T}^j - x\langle\Delta p_{\rm T}^j\rangle)\right)$$

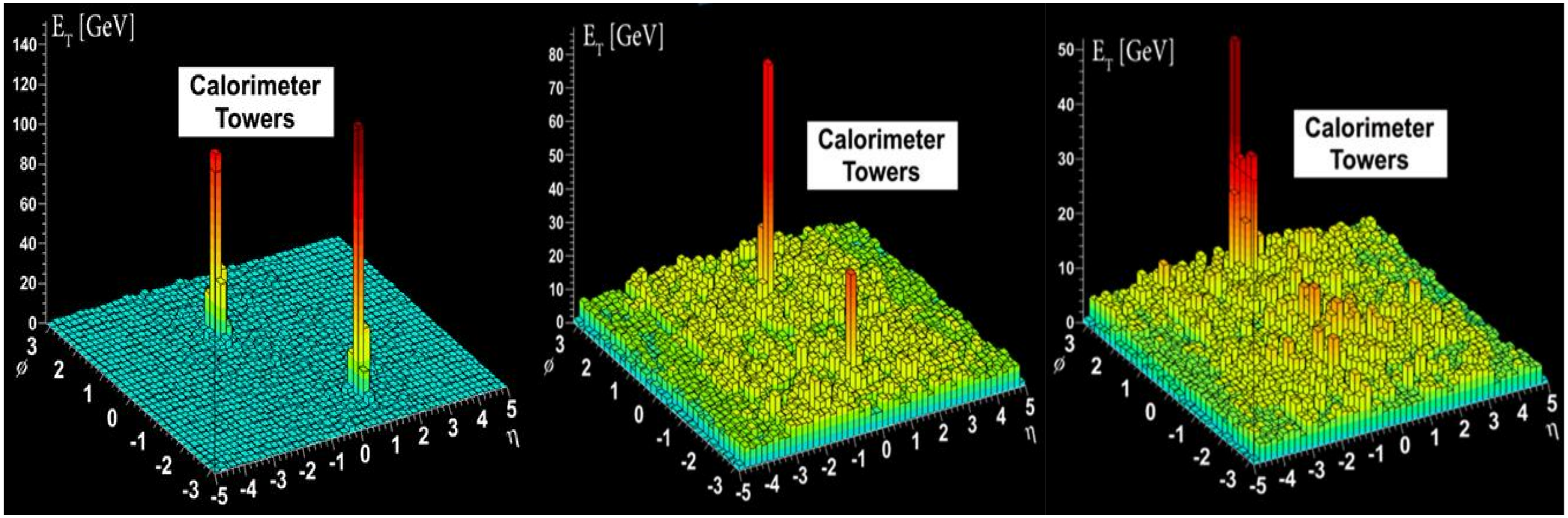
$$\langle \Delta E_g\rangle > \langle \Delta E_q\rangle \sim \langle \Delta E_c\rangle > \langle \Delta E_b\rangle$$

Direct extraction of the flavor dependence of parton energy loss in QGP from data.

Provides a stringent test of pQCD calculation of parton-medium interaction.

W. J. Xing, S. Cao, GYQ, arXiv:2303.12485

Medium response



How does the medium respond to the lost energy?

How does the lost energy redistribute and manifest in final state?

Where to search for the signal of medium response?

How to use medium response to probe the medium properties?

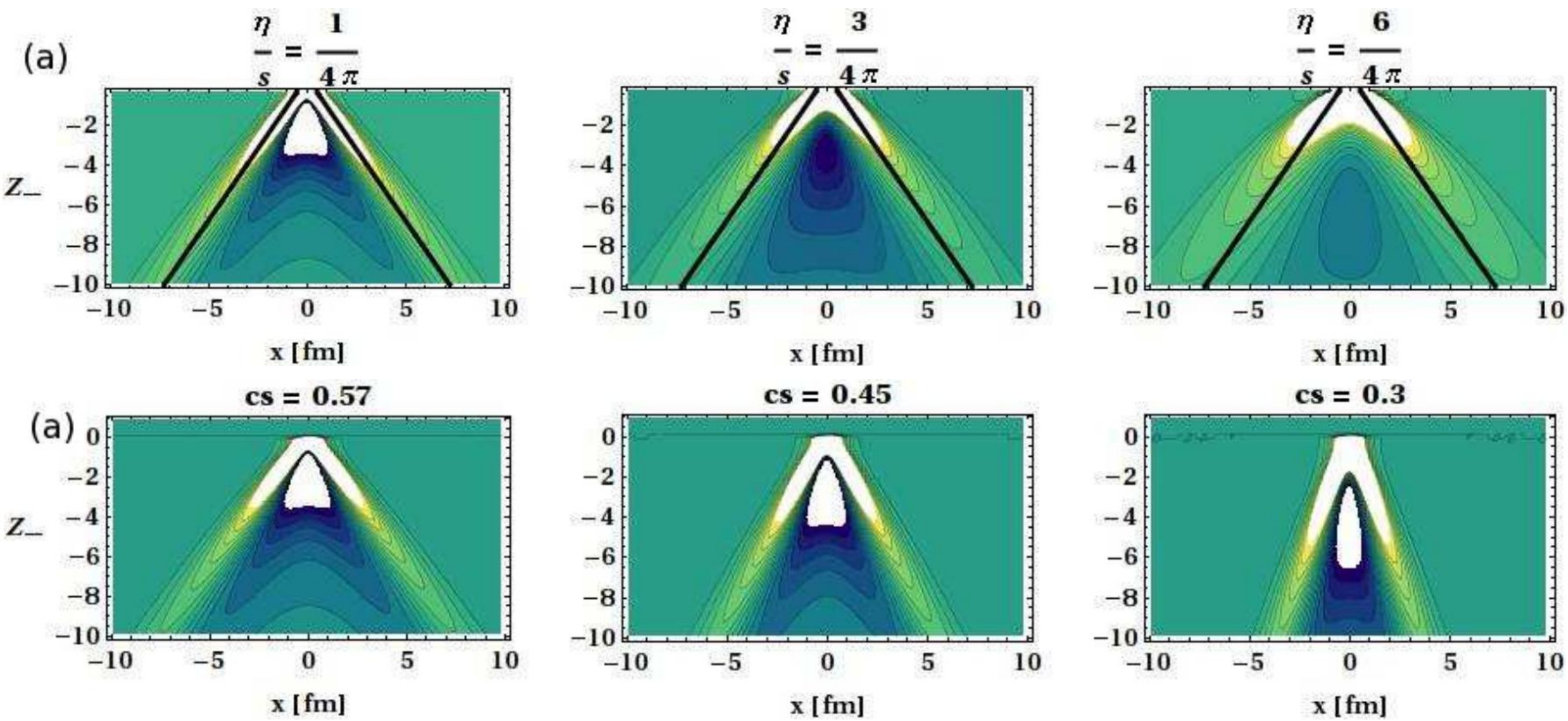
Earlier works on medium response

$$T^{\mu\nu} \simeq T_0^{\mu\nu} + \delta T^{\mu\nu}; \quad \partial_\mu T_0^{\mu\nu} = 0, \quad \partial_\mu \delta T^{\mu\nu} = J^\nu.$$

$$\delta T^{00} \equiv \delta\epsilon, \qquad \delta T^{0i} \equiv g^i,$$

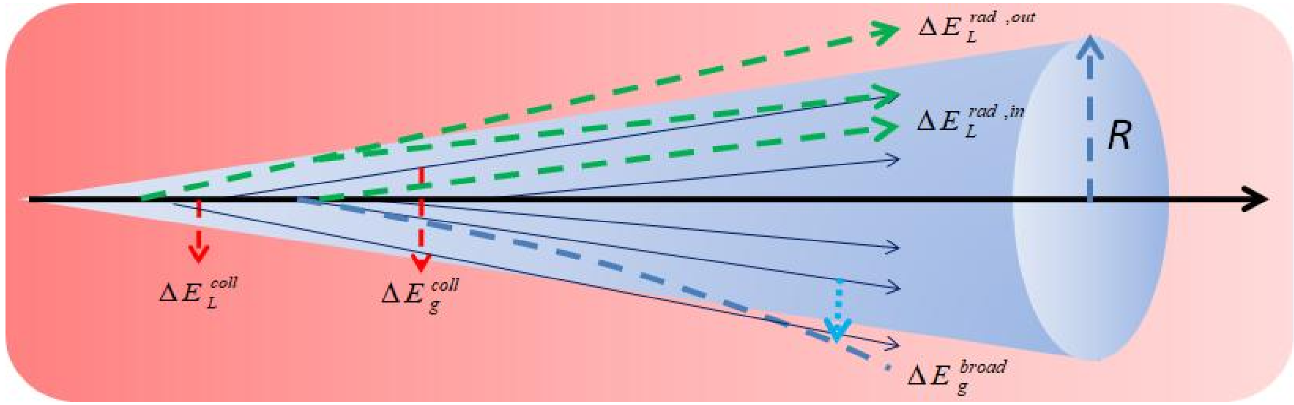
$$\delta T^{ij} = \delta_{ij} c_s^2 \delta\epsilon - \Gamma_s(\partial^i g^j + \partial^j g^i - \tfrac{2}{3}\delta_{ij}\nabla\cdot\vec{g}).$$

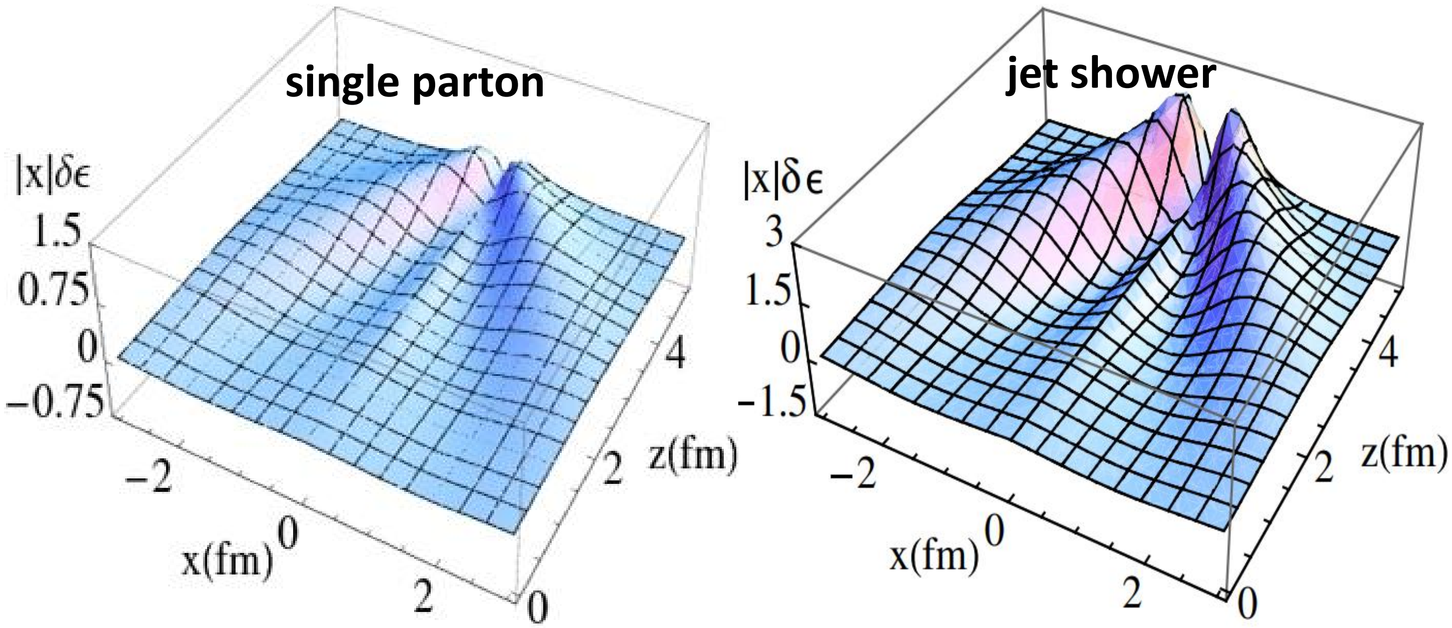
Casalderrey-Solana, Shuryak, Teaney, hep-ph/0411315; Stoecker, nucl-th/0406018; Ruppert, Muller, PLB 2005; ...



Neufeld, PRC 2009

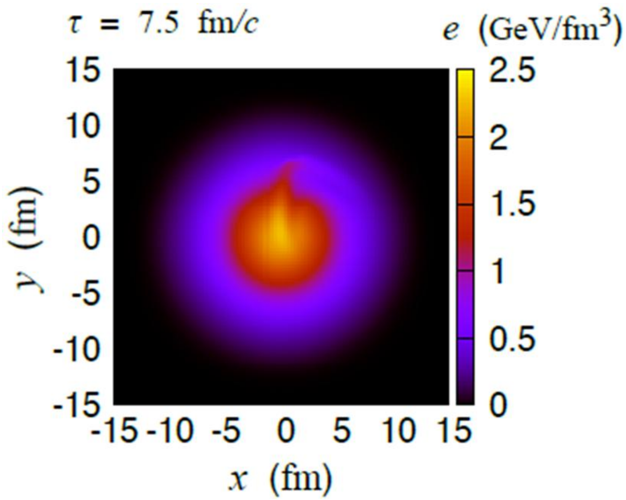
Medium response to jet shower

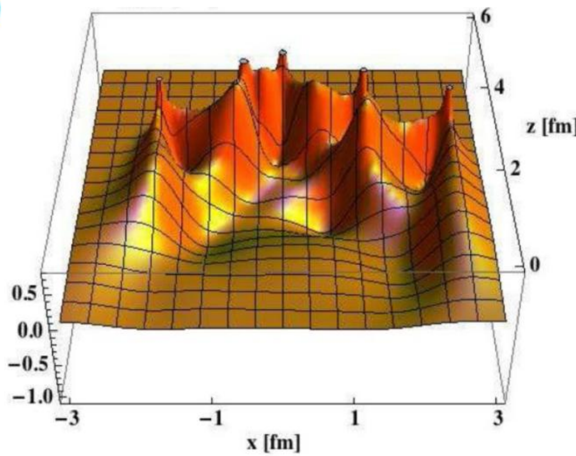


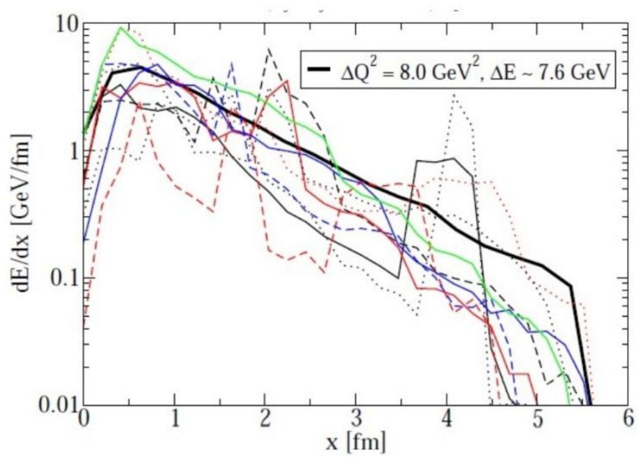


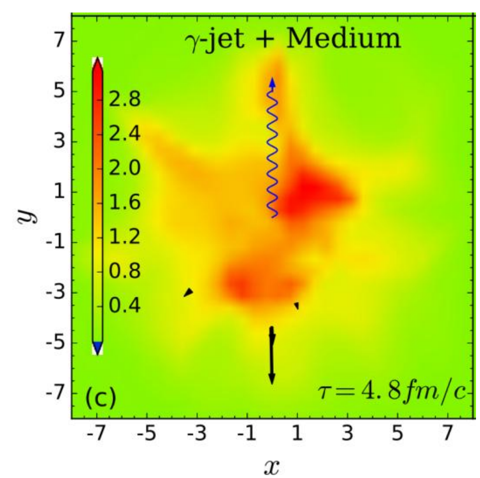
GYQ, Majumder, Song, Heinz, PRL 2009; Neufeld, Muller, PRL 2009

Complications









The flow of the expanding medium can distort the conic structure

Detailed distributions of the energy and momentum deposition profiles

Even-by-event fluctuations of jet shower evolution and energy loss

Large and event-by-event fluctuating background medium

Neufeld, Vitev, PRC 2012; Renk, PRC 2013; Tachibana, Chang, GYQ, PRC 2017; Chen, Cao, Luo, Pang, Wang, PLB 2018

Treatments on medium response

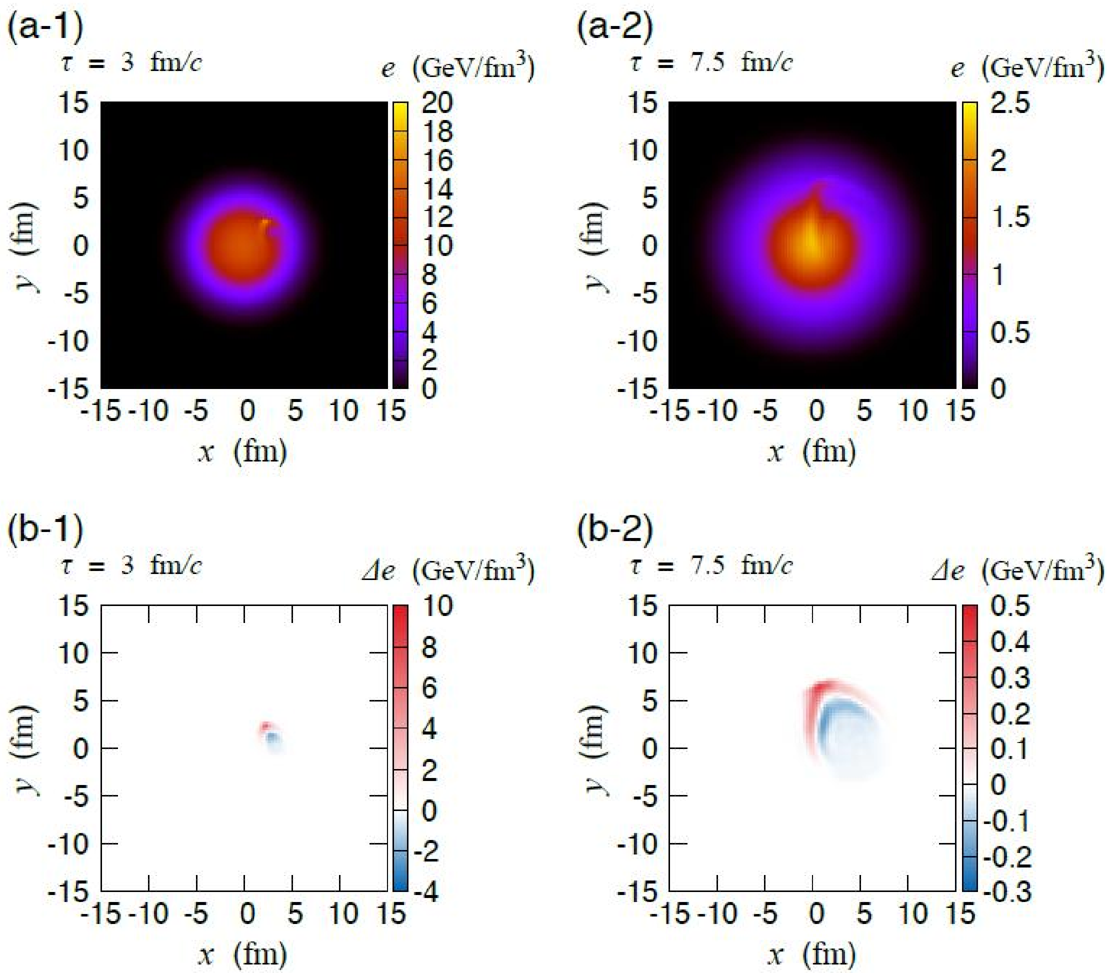
- Jet + recoil
  - LBT (He, Luo, Cao, Zhu, Wang, et al, 1503.03313; 1803.06785)
  - JEWEL (Elayavalli, Zapp, Milhano, Wiedemann, 1707.01539; 1707.04142)
  - MARTINI (Park, Jeon, Gale, 1807.06550)

- Jet + hydrodynamics
  - Coupled Jet-Fluid Model (Tachibana, Chang, GYQ: 1701.07951; 1906.09562)
  - CoLBT-Hydro (Chen, Yang, Luo, He, Cao, Ke, Pang, Wang, et al, 1704.03648; 2005.09678; 2101.05422; 2203.03683)
  - JETSCAPE (2002.12250)
  - Minijet+Hydro (Pablos, Singh, Jeon and Gale, 2202.03414)
  - Hybrid Model (Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, 1609.05842)

- Full Boltzmann
  - AMPT (Gao, Luo, Ma, Mao, GYQ, Wang, Zhang, 1612.02548; 2107.11751; 2109.14314)
  - BAMPS (Bouras, Betz, Xu, Greiner, 1201.5005; 1401.3019)

- See Cao, GYQ, 2211.16821 [nucl-th] (https://doi.org/10.1146/annurev-nucl-112822-031317) for a recent review.

Jet evolution & medium response



$$\frac{df}{dt} = C[f],\ \partial_\mu T^{\mu\nu} = J^\nu$$

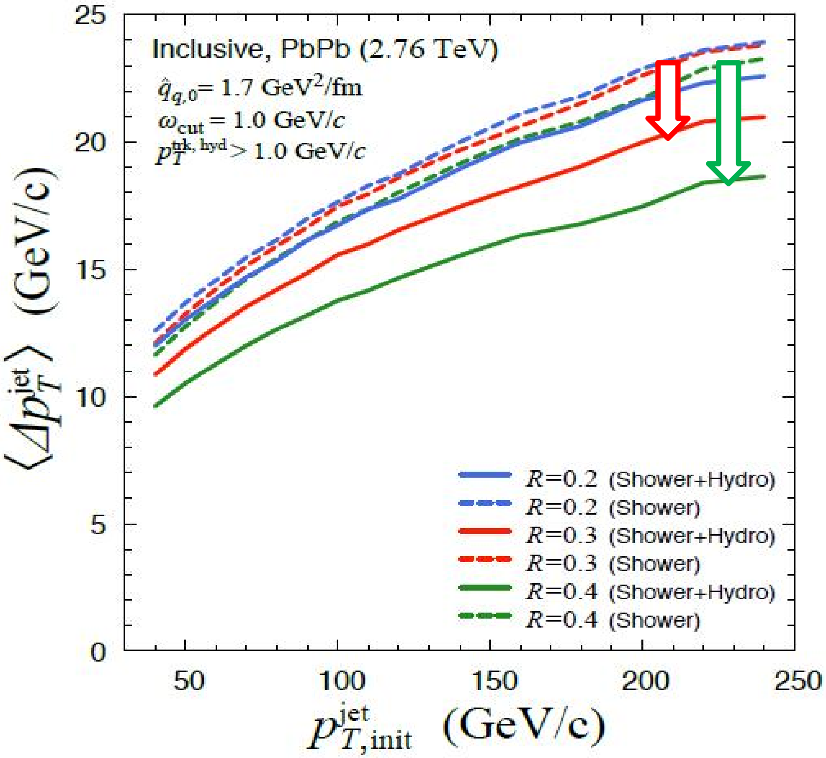
Jet deposits energy and momentum into medium, and induces V-shaped wave fronts

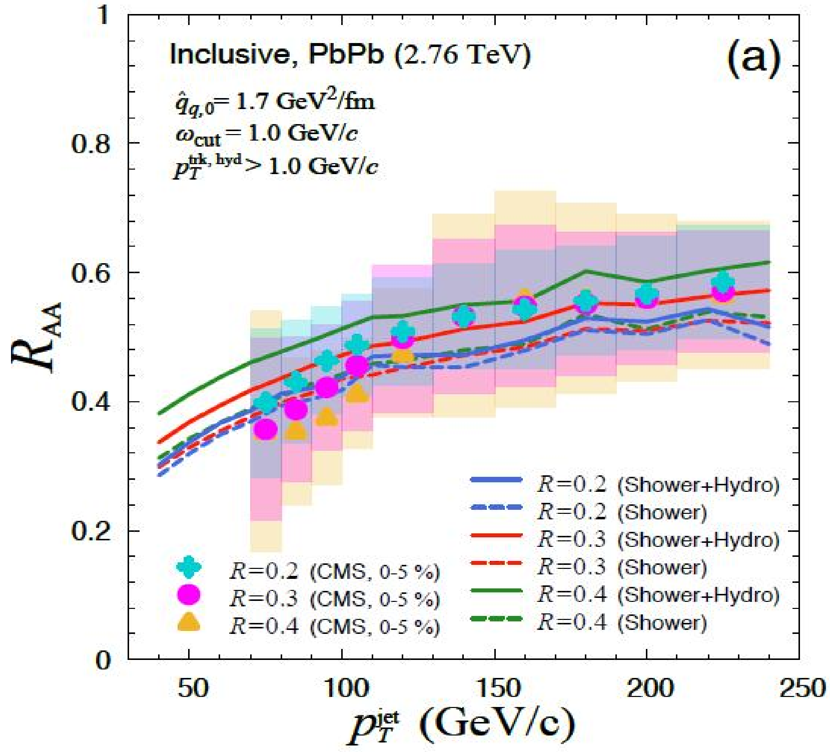
The wave fronts carry energy and momentum, propagates forward and outward, and depletes the energy behind the jet (diffusion wake)

Jet-induced flow and the radial flow of medium are pushed and distorted by each other

Chang, GYQ, PRC 2016; Tachibana, Chang, GYQ, PRC 2017; Chang, Tachibana, GYQ, PLB 2020

Medium response effect on ΔE & R_{AA}

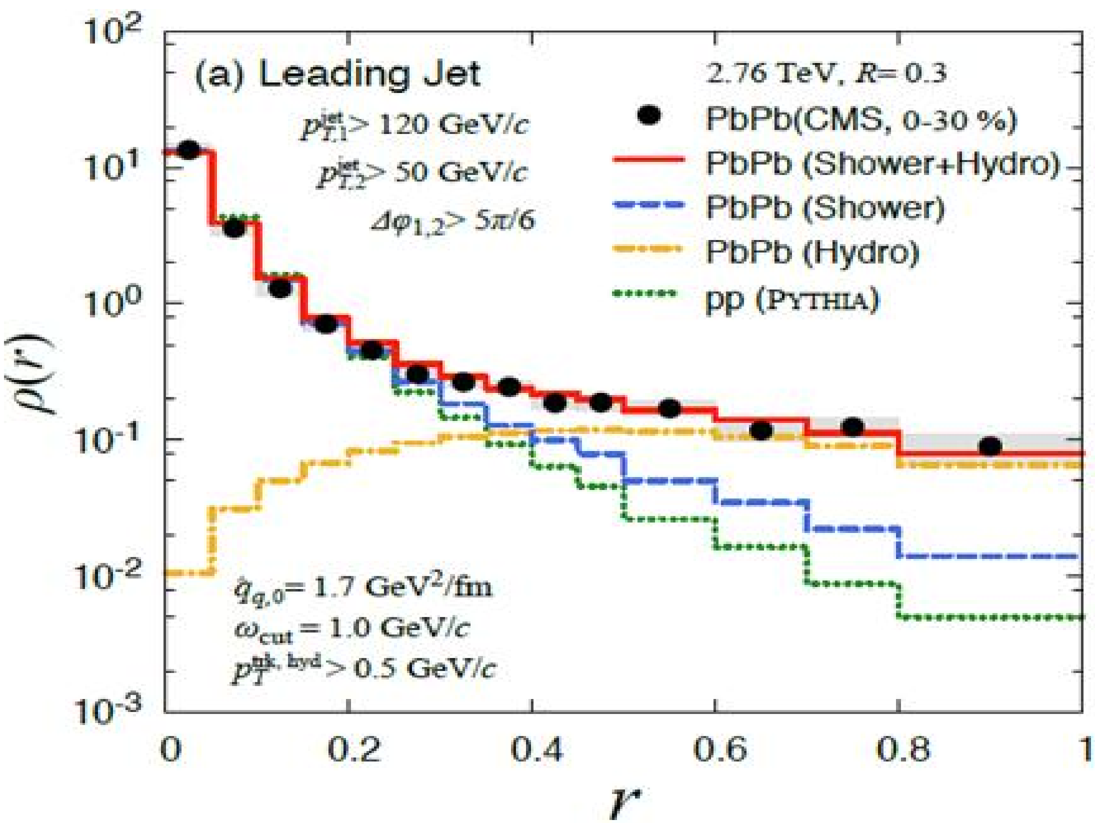


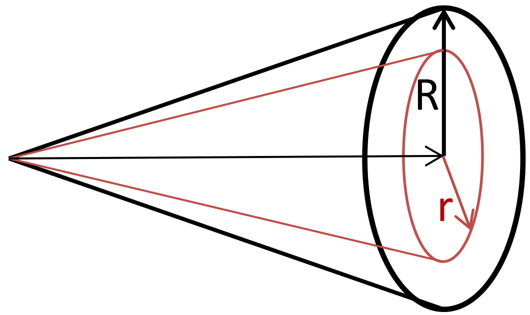


Hydro part partially compensates the energy loss experienced by jet shower part.
Jet-induced flow evolves with medium, diffuses, and spreads widely around jet axis, leading to stronger jet cone size dependence.

Chang, GYQ, PRC 2016; Tachibana, Chang, GYQ, PRC 2017; Chang, Tachibana, GYQ, PLB 2020

Redistribution of lost energy from quenched jets

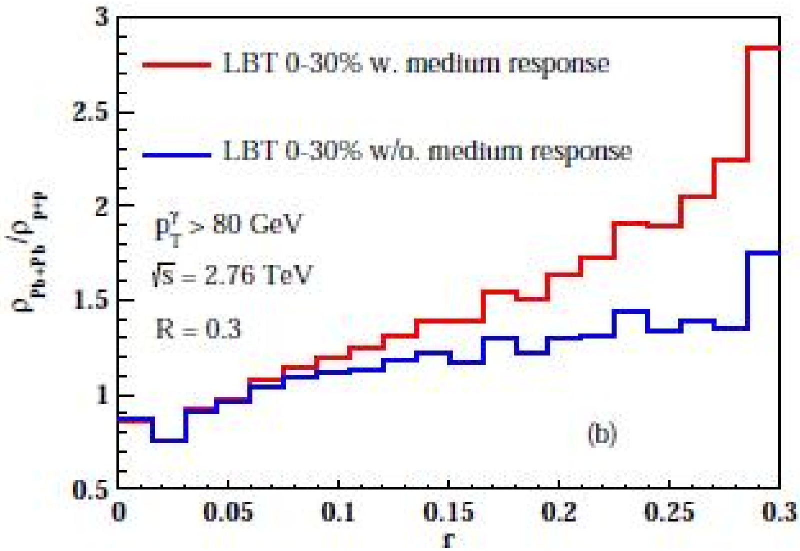


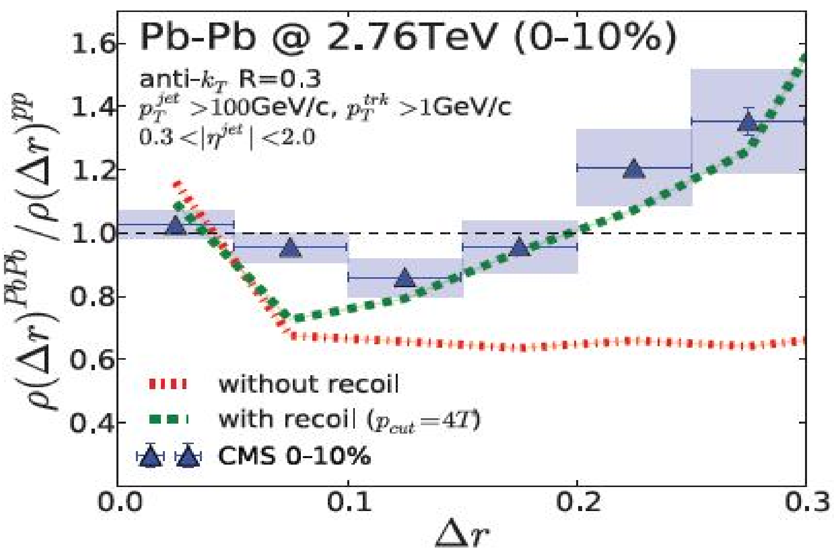


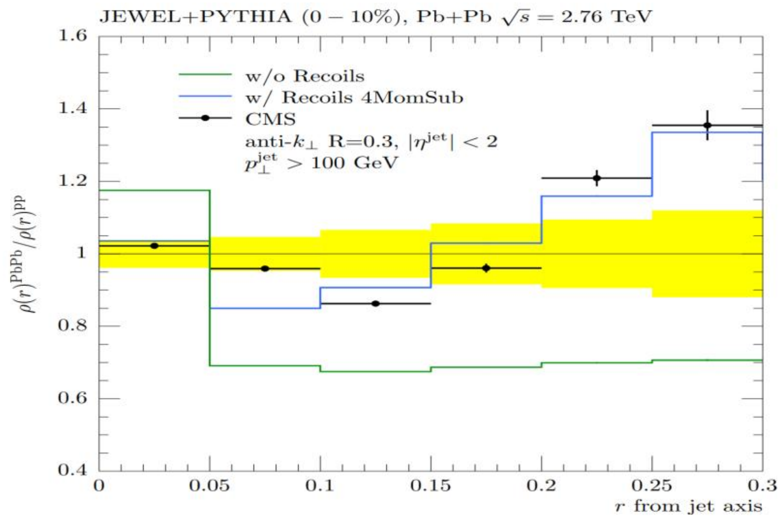
The contribution from the hydro part is quite flat and finally dominates over the shower part in the region from r = 0.4-0.5.
Signal of jet-induced medium excitation in full jet shape at large r.

Chang, GYQ, PRC 2016; Tachibana, Chang, GYQ, PRC 2017; Chang, Tachibana, GYQ, PLB 2020

Other similar results on medium response





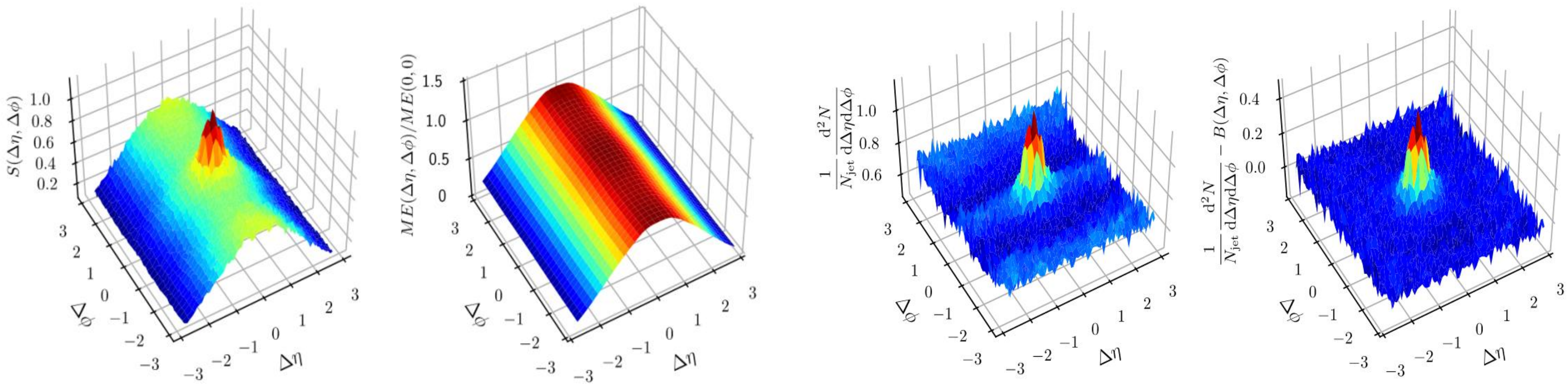


Luo, Cao, He, Wang, PLB 2018;
C. Park, S. Jeon, C. Gale, 2018;
Elayavalli, Zapp, JHEP 2017;

The inclusion of medium response can naturally explains the enhancement of jet shape at larger radius.

Hadron chemistry around quenched jets

The particles (their spectra and chemical compositions) produced from jet-excited energy should be different from those from vacuum-like energy.



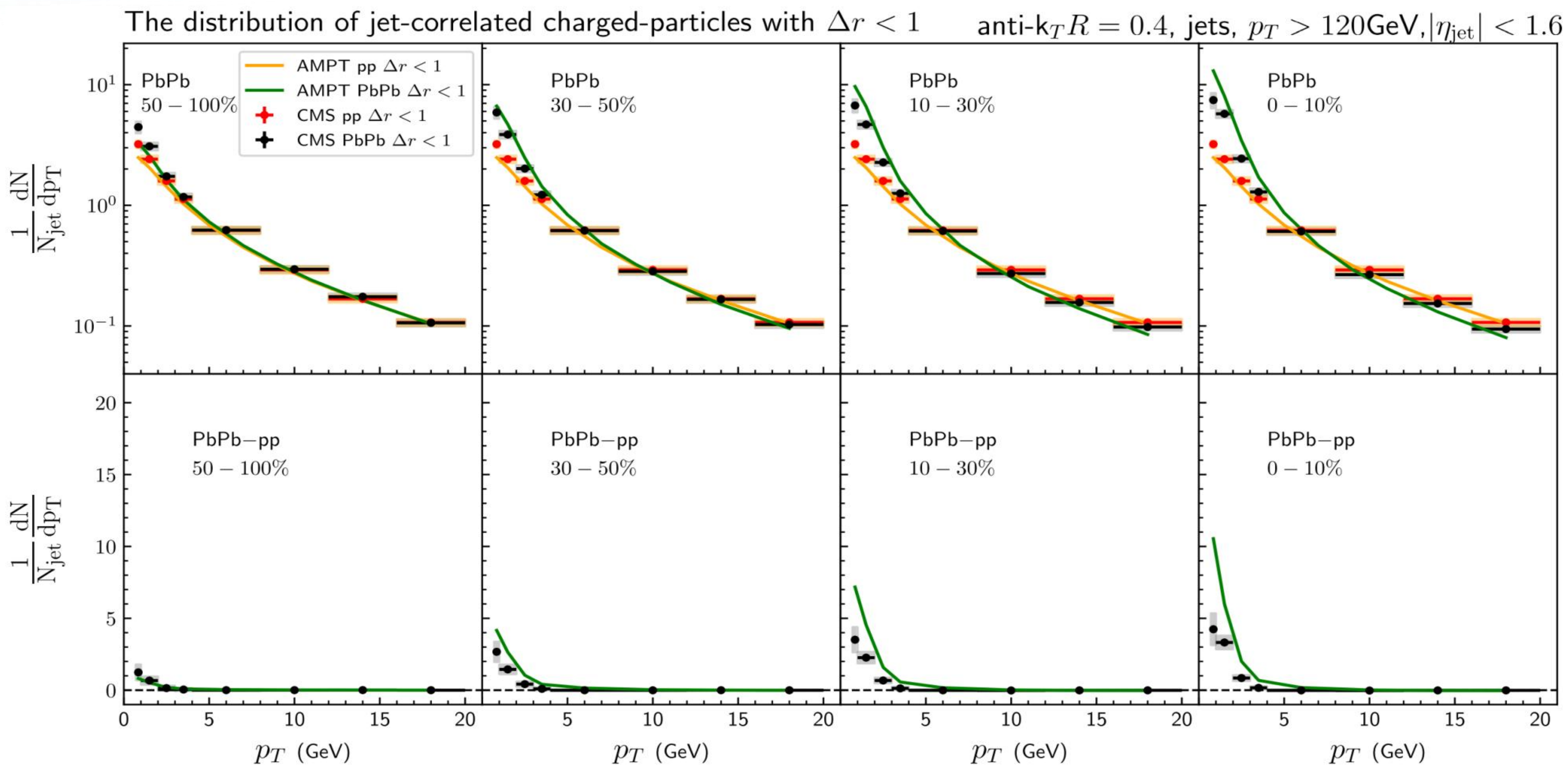
$$\frac{1}{N_{\text{jet}}}\frac{d^2N}{d\Delta\eta d\Delta\phi} = \frac{ME(0,0)}{ME(\Delta\eta,\Delta\phi)}S(\Delta\eta,\Delta\phi) \quad \Rightarrow \quad \frac{d^3N}{dp_T d\Delta\phi d\Delta\eta}$$

$$\frac{dN}{dp_T} = \int d\Delta\phi \int d\Delta\eta \frac{d^3N}{dp_T d\Delta\phi d\Delta\eta}\bigg|_{\Delta r<1}$$

$$\frac{dN}{d\Delta r} = \int d\Delta\phi \int d\Delta\eta \int dp_T \frac{d^3N}{dp_T d\Delta\phi d\Delta\eta}\delta(\Delta r - \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2})$$

Luo, Mao, GYQ, Wang, Zhang, PLB 2023

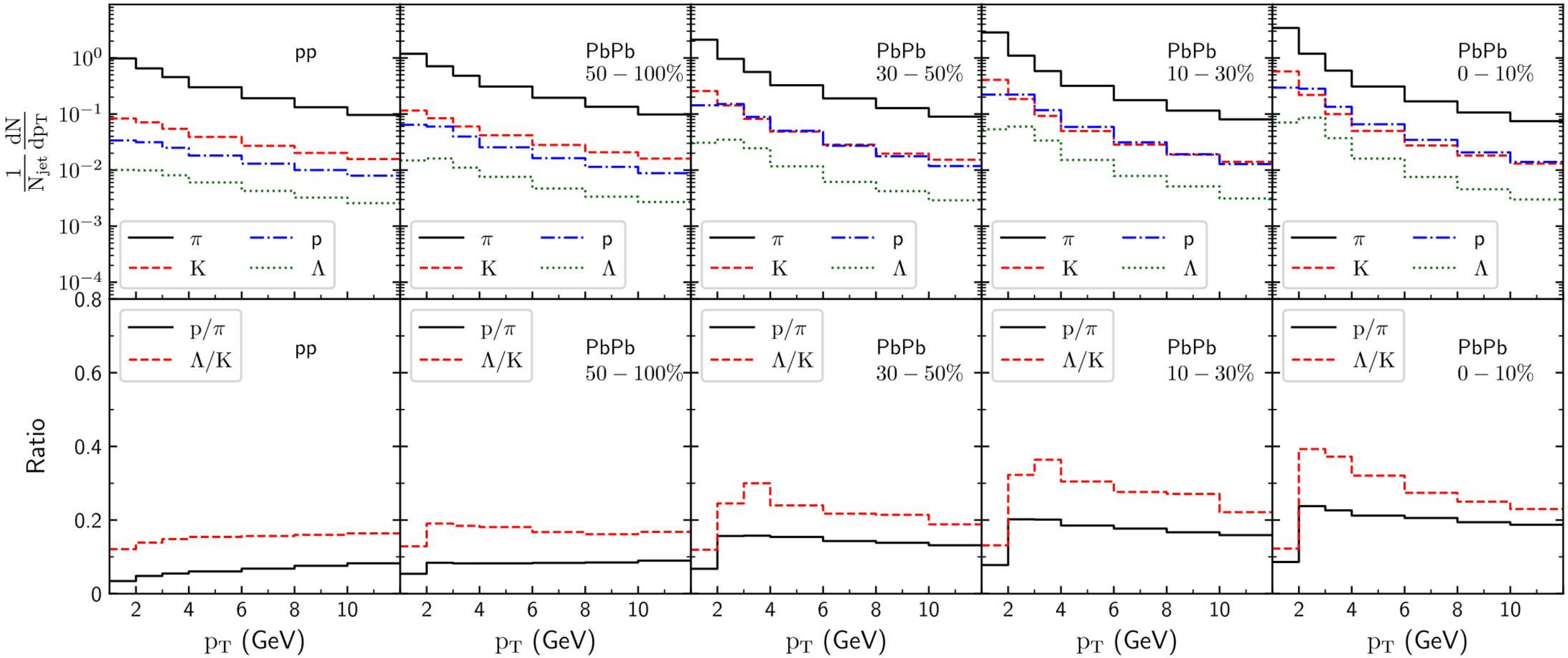
Jet-induced particle yield around jets



Jet quenching leads to the enhancement of soft particles and the suppression of hard particles around the jets. Such effect is more pronounced for more central collisions.

Luo, Mao, GYQ, Wang, Zhang, EPJC 2022

B/M enhancement at intermediate p_T around jets

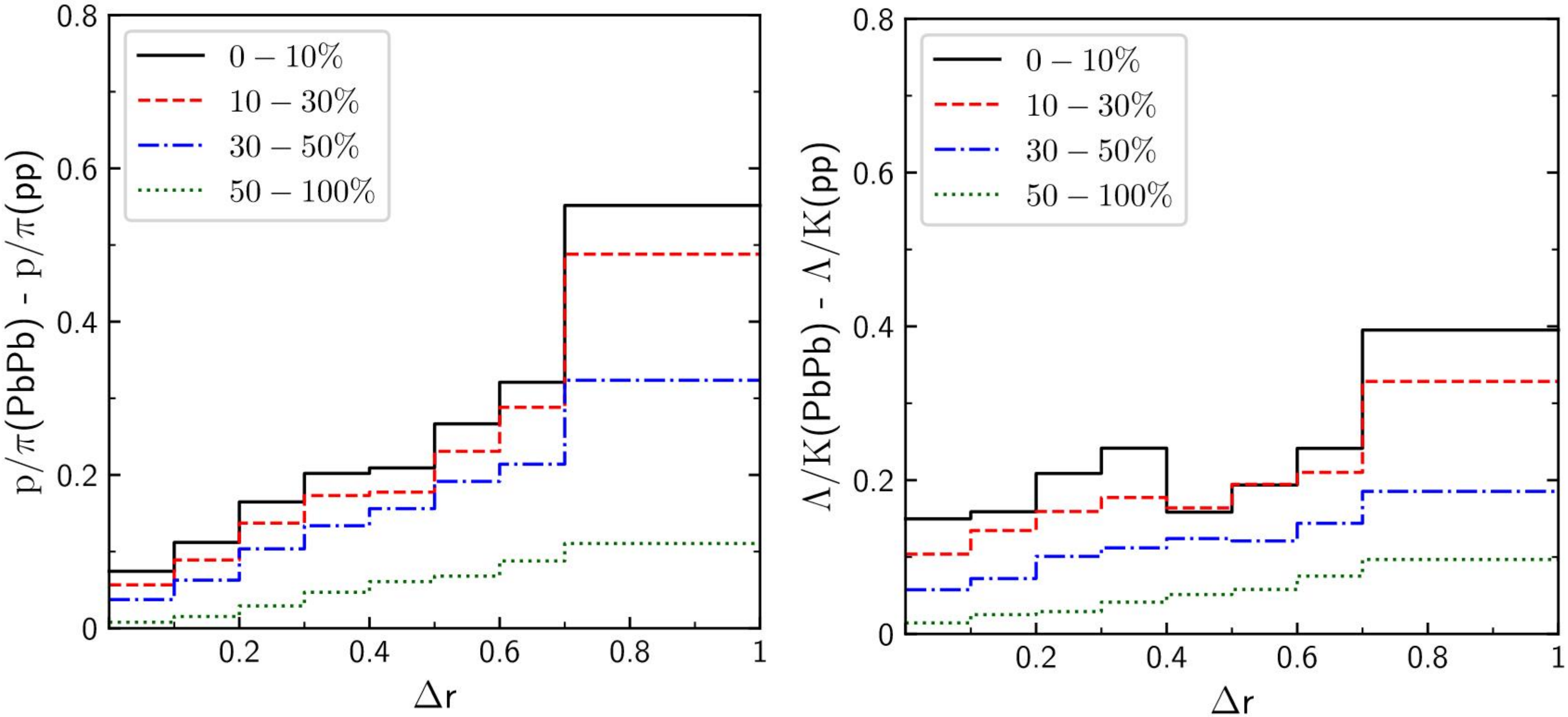


Using jet-particle correlations (with mixed event and side band procedures), we study identified particle production around the quenched jets.

Strong enhancement of B/M ratios for associated particles at intermediate p_T around the quenched jets, due to the coalescence of jet-excited medium partons.

Luo, Mao, GYQ, Wang, Zhang, PLB 2023

B/M enhancement around jets: radial dependence



For intermediate p_T (2-6GeV) regime, the enhancement of jet-induced B/M ratios is stronger for larger distance because the lost energy from quenched jets can diffuse to large angle.

Luo, Mao, GYQ, Wang, Zhang, PLB 2023

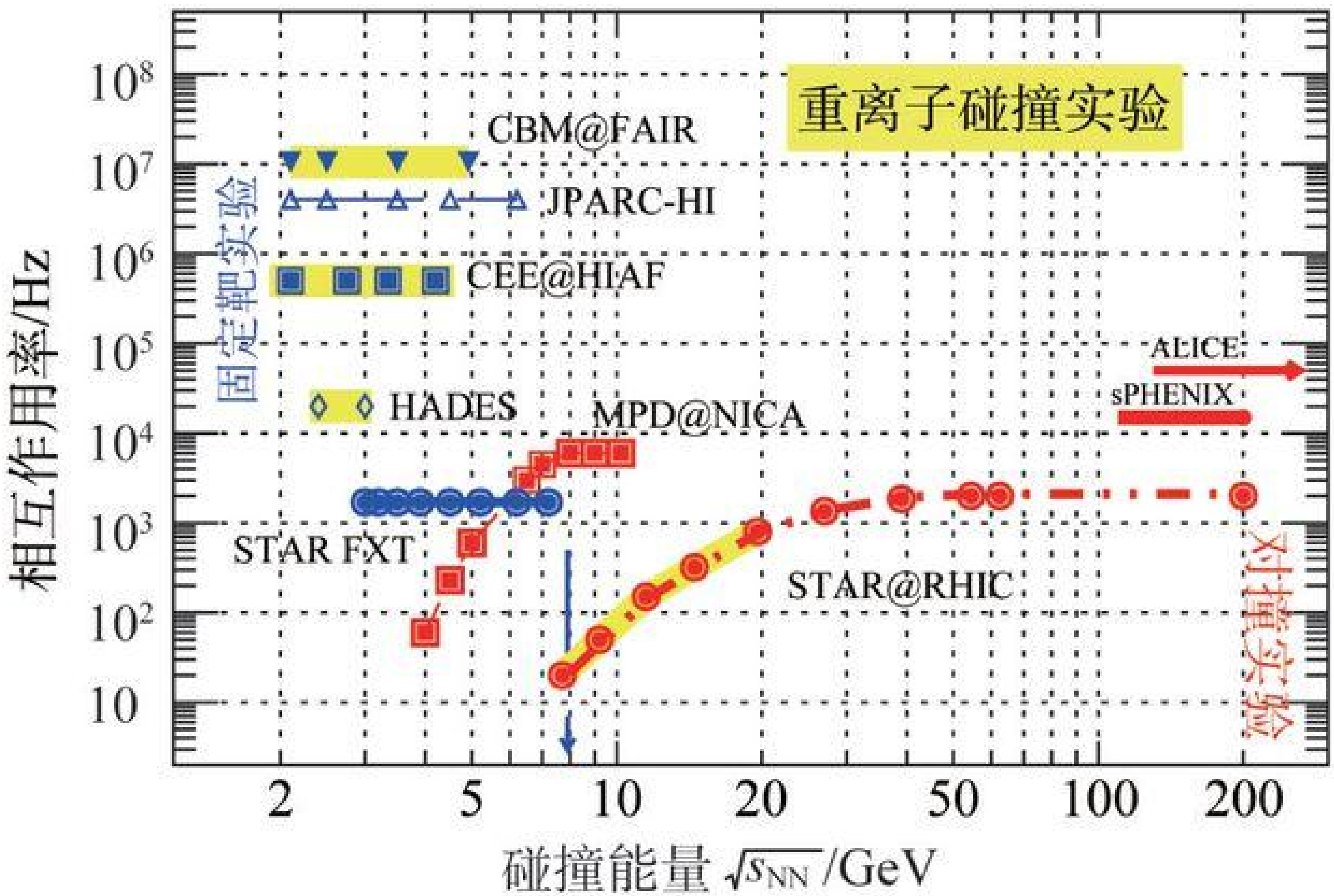
Summary

- **Jet quenching**
  - The state-of-the-art framework (NLO + LBT + Hydro) can explain the flavor hierarchy of jet quenching
  - Gluon jet quenching dominates high p_T J/Ψ suppression
  - Bayesian extraction of gluon, light quark & HQ energy loss

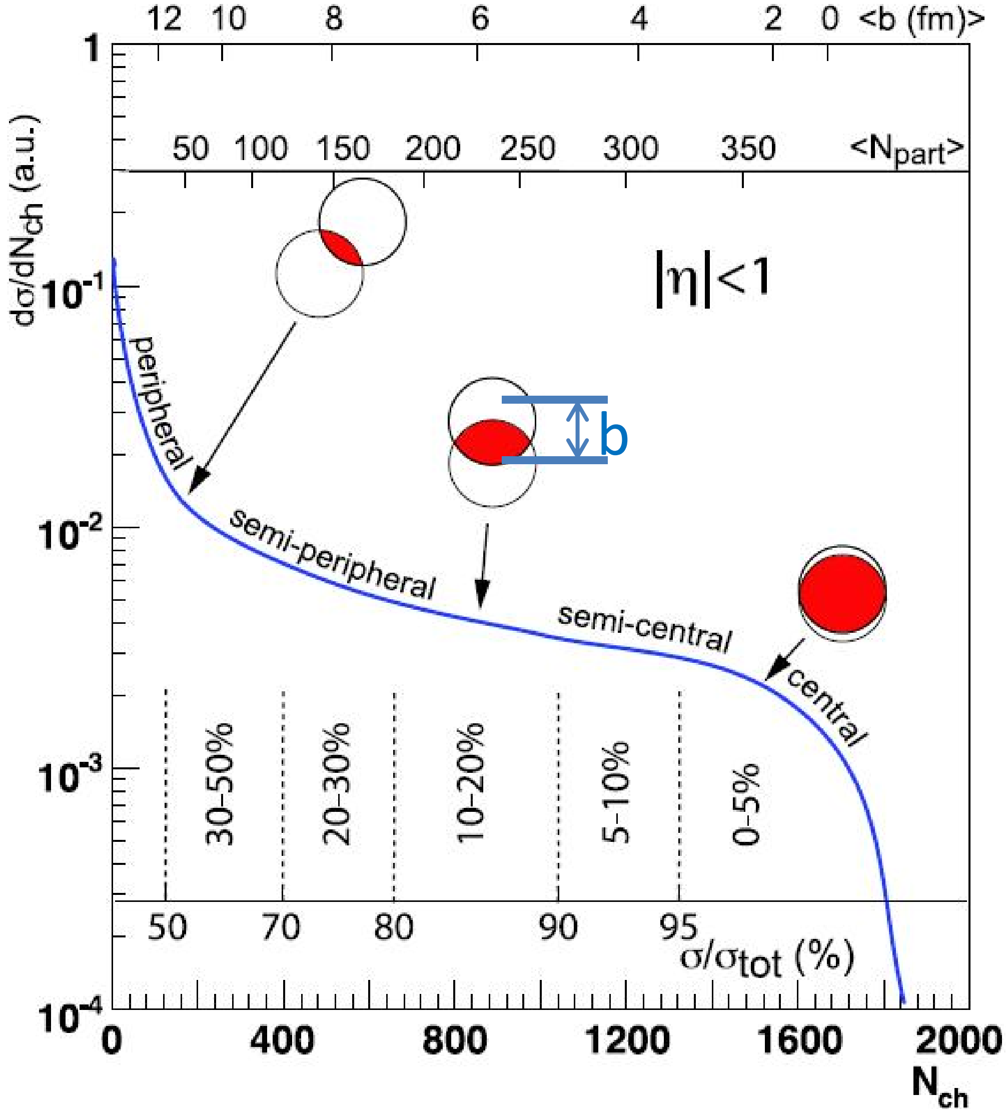
- **Medium response:**
  - The jet-fluid model shows medium response signal in jet shape at large r
  - Propose B/M enhancement around jets as a signal of medium response

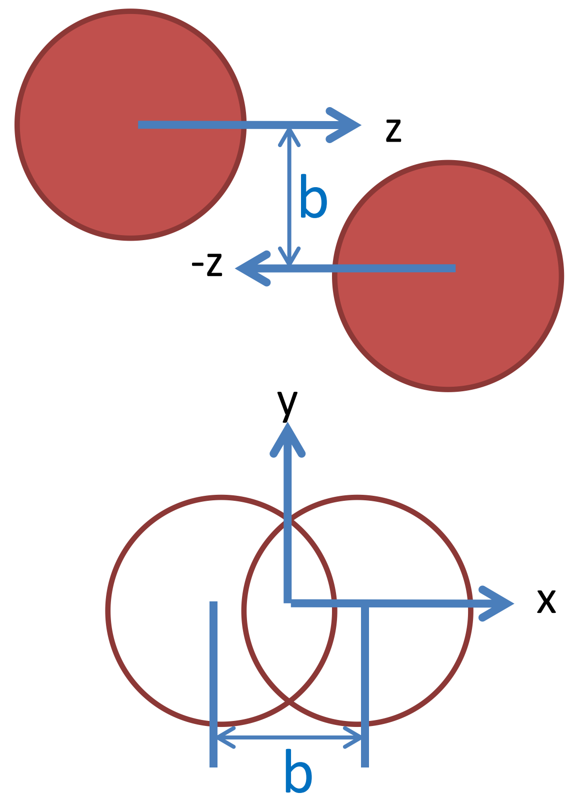
Backup slides

Relativistic heavy-ion experiments



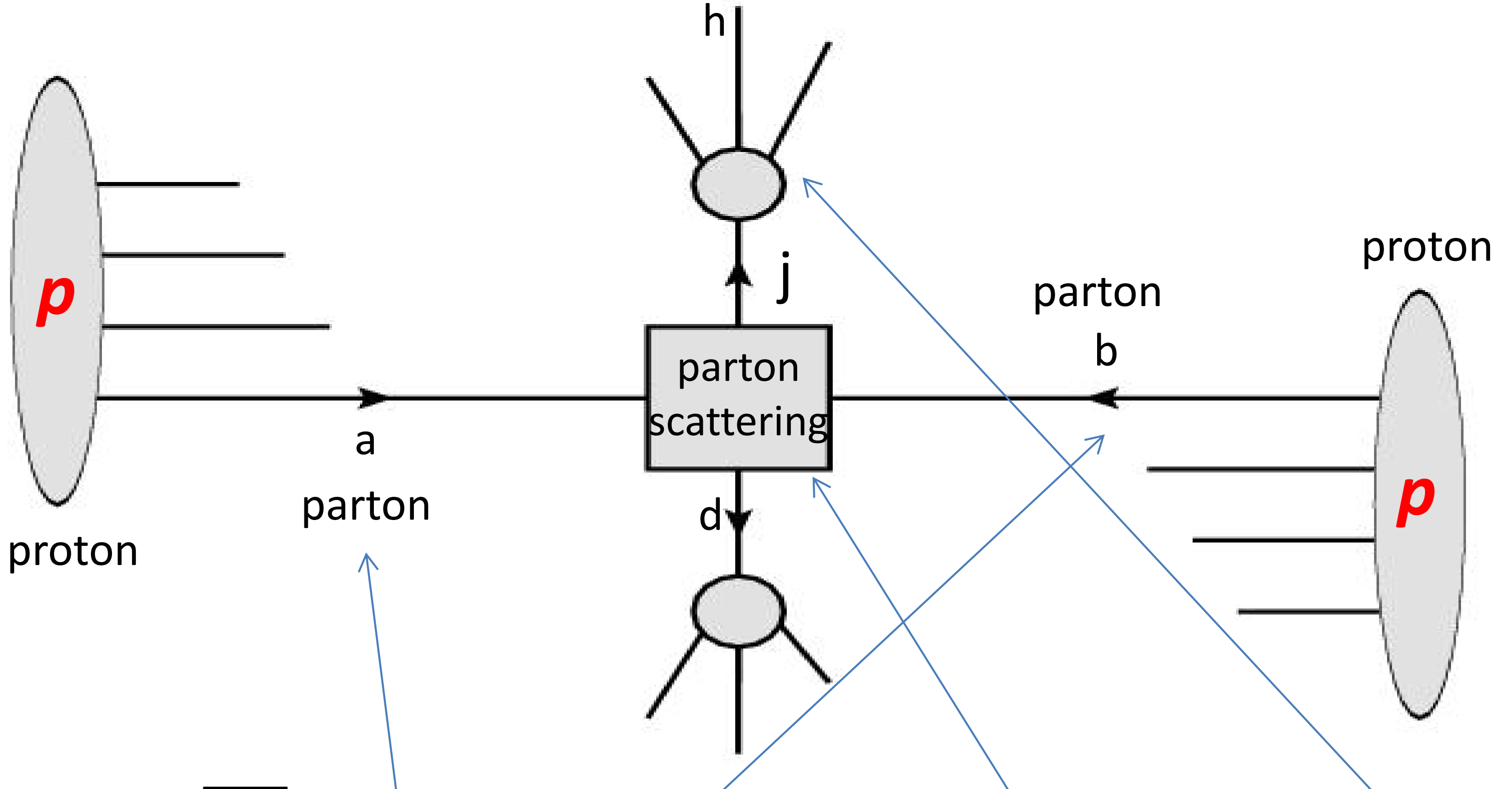
Collision centrality





Miller, Reygers, Sanders, Steinberg, Ann. Rev. Nucl. Part. Sci. 57 (2007) 205-243

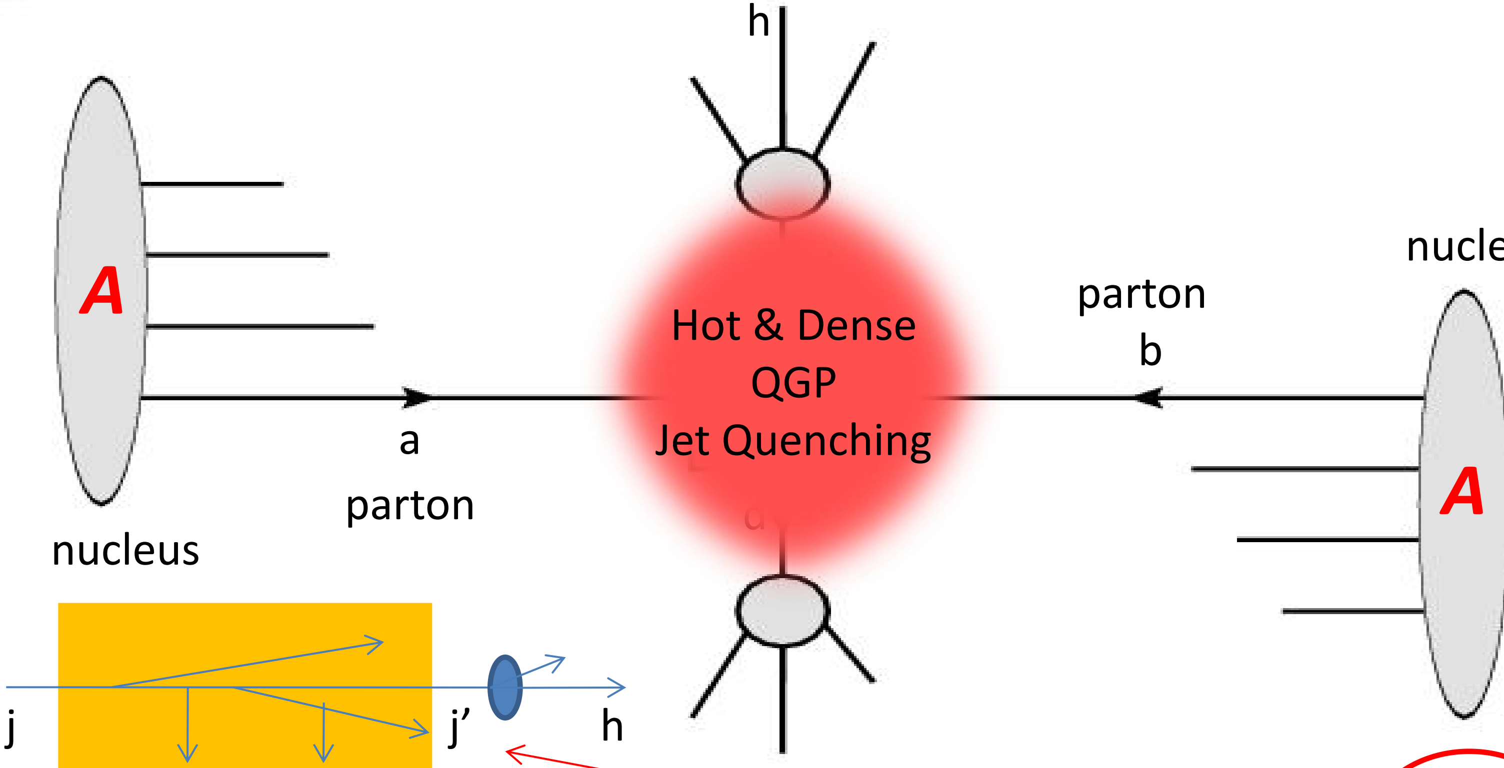
Leading hadron production in pp collisions



$$d\sigma_h = \sum_{abj} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\to jX} \otimes D_{h/j}$$

pQCD factorization: Large-p_T processes may be factorized into long-distance pieces in terms of PDF & FF, and short-distance parts describing hard interactions of partons.

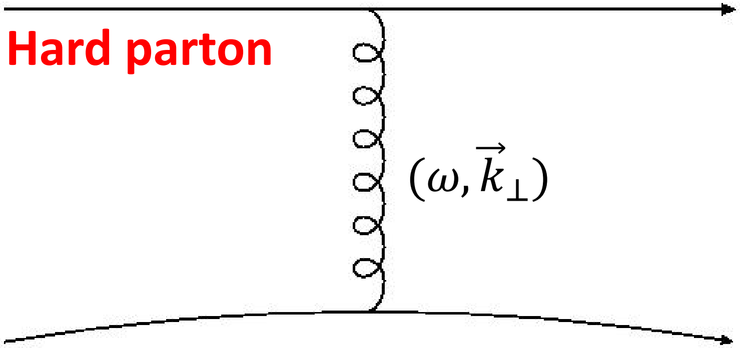
Leading hadron production in AA collisions



$$d\tilde{\sigma}_h = \sum_{abjX} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\to jX} \otimes \tilde{D}_{h/j}$$

$$d\tilde{\sigma}_h = \sum_{abjj'} f_a \otimes f_b \otimes d\sigma_{ab\to jX} \otimes P_{j\to j'} \otimes D_{h/j'}$$

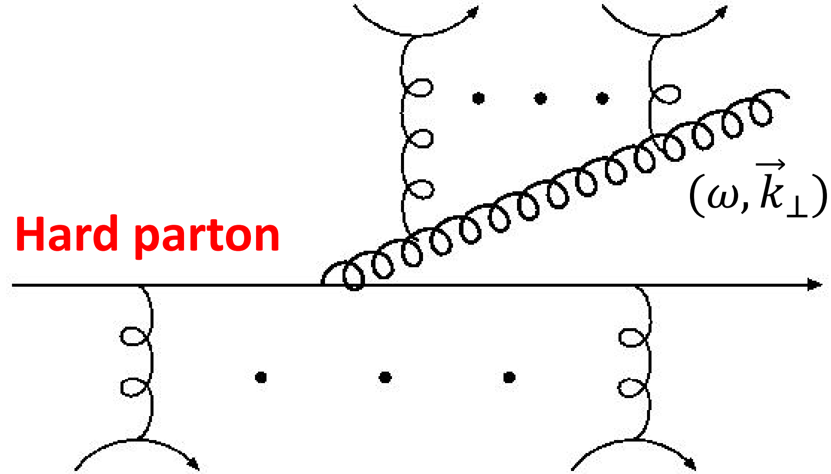
Jet-medium interaction



Elastic (collisional)

$$\frac{d\Gamma_{coll}}{d\omega dk_\perp^2 dt}(T, E, \ldots) = ?$$

Bjorken 1982; Bratten, Thoma 1991; Thoma, Gyulassy, 1991; Mustafa, Thoma 2005; Peigne, Peshier, 2006; Djordjevic, 2006; Wicks et al (DGLV), 2007; GYQ et al (AMY), 2008; …



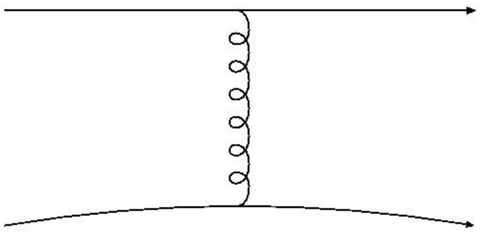
Inelastic (radiative)

$$\frac{d\Gamma_{rad}}{d\omega dk_\perp^2 dt}(T, E, \ldots) = ?$$

BDMPS-Z: Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov
ASW: Amesto-Salgado-Wiedemann
AMY: Arnold-Moore-Yaffe (& Caron-Huot, Gale)
GLV: Gyulassy-Levai-Vitev (& Djordjevic, Heinz)
HT: Wang-Guo (& Zhang, Wang, Majumder, GYQ)

Collisional energy loss

- From kinetic theory:



$$\frac{dE}{dt} = \frac{g_k}{2E}\int\frac{d^3k}{(2\pi)^3 2k}\int\frac{d^3p'}{(2\pi)^3 2E'}\int\frac{d^3k'}{(2\pi)^3 2k'}$$
$$(2\pi)^4\delta^4(P+K-P'-K')(E-E')|\bar{M}|^2 f(k)[1\pm f(k')]$$

- It is infrared logarithmic divergent, screened by plasma effects which are incorporated by including hard thermal loop corrections for soft momenta of order gT

- The collisional energy loss rate for different channels:

$$\left.\frac{dE}{dt}\right|_{qq} = \frac{2}{9}n_f\pi\alpha_s^2T^2\left[\ln\frac{ET}{m_g^2}+c_f+\frac{23}{12}+c_s\right]$$

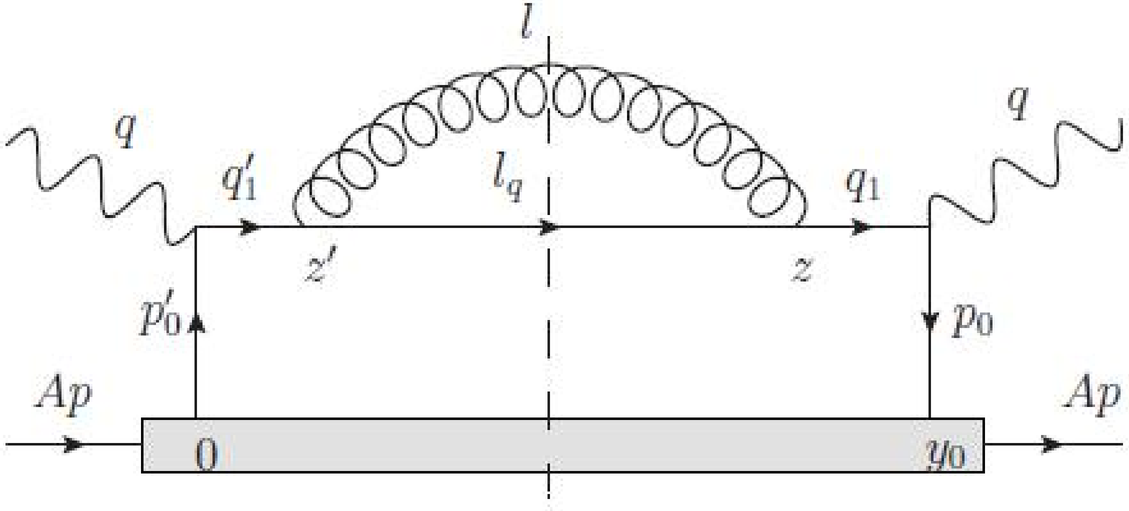
$$\left.\frac{dE}{dt}\right|_{qg} = \frac{4}{3}\pi\alpha_s^2T^2\left[\ln\frac{ET}{m_g^2}+c_b+\frac{13}{6}+c_s\right]$$

$$\left.\frac{dE}{dt}\right|_{gq} = \frac{1}{2}n_f\pi\alpha_s^2T^2\left[\ln\frac{ET}{m_g^2}+c_f+\frac{13}{6}+c_s\right]$$

$$\left.\frac{dE}{dt}\right|_{gg} = 3\pi\alpha_s^2T^2\left[\ln\frac{ET}{m_g^2}+c_b+\frac{131}{48}+c_s\right]$$

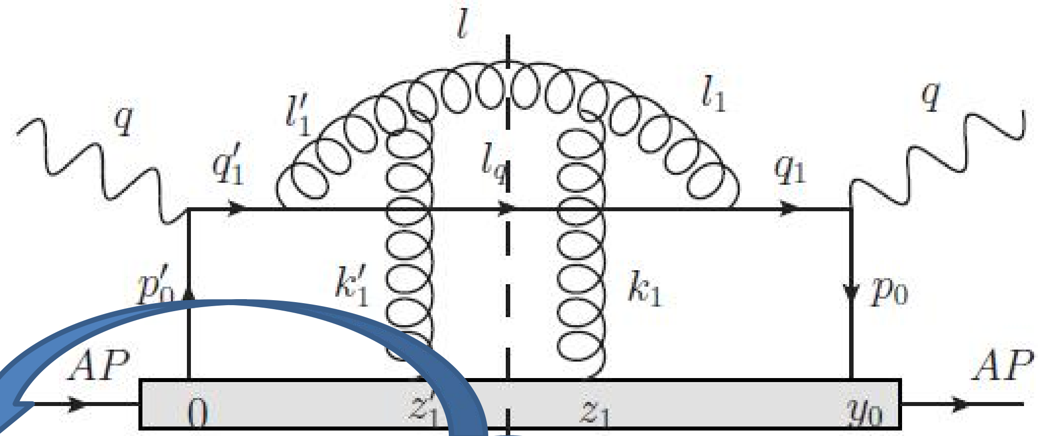
Bjorken 1982; Bratten, Thoma 1991; Thoma, Gyulassy, 1991; Mustafa, Thoma 2005; Peigne, Peshier, 2006; Djordjevic (GLV), 2006; Wicks et al (DGLV), 2007; GYQ et al (AMY), 2008

Gluon emission in vacuum



$$\frac{dN_g^{\rm vac}}{dy\, d^2\mathbf{l}_\perp} = C_F \frac{\alpha_s}{2\pi^2} P(y) \frac{l_\perp^2 + \frac{y^4}{1+(1-y)^2} M^2}{(l_\perp^2 + y^2 M^2)^2}.$$

Medium-induced radiation



Zhang, Hou, GYQ, PRC 2018 & PRC 2019; Zhang, GYQ, Wang, PRD 2019.

+ other 20 diagrams

$$\frac{dN_g^{med}}{dy\,d^2\mathbf{l}_\perp} = \frac{\alpha_s}{2\pi^2}P(y)\int dZ_1^- \int \frac{dk^- d^2\mathbf{k}_{1\perp}}{(2\pi)^3}\mathcal{D}(k_1^-, \mathbf{k}_{1\perp})$$

$$\times\left\{\left[2 - 2\cos\left(\frac{y(1-y)}{(y-\lambda_1^-)(1+\lambda_1^- - y)}\frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2M^2}{l_\perp^2 + y^2M^2}\frac{Z_1^-}{\tilde{\tau}^-_{\text{form}}}\right)\right]\right.$$

$$C_A\left[\frac{1+(1+\lambda_1^- - y)^2}{1+(1-y)^2}\left(\frac{y-\frac{\lambda_1^-}{2}}{y-\lambda_1^-}\right)^2 \frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + \frac{(y-\lambda_1^-)^4M^2}{1+(1+\lambda_1^- - y)^2}}{[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2M^2]^2}\right.$$

$$-\frac{1+(1+\lambda_1^- - y)(1-y)}{2[1+(1-y)^2]}\left(\frac{y-\frac{\lambda_1^-}{2}}{y-\lambda_1^-}\right)\frac{\mathbf{l}_\perp\cdot(\mathbf{l}_\perp - \mathbf{k}_{1\perp}) + \frac{y^2(y-\lambda_1^-)^2}{1+(1+\lambda_1^- - y)(1-y)}M^2}{[l_\perp^2 + y^2M^2]\,[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2M^2]}$$

$$-\frac{1+(1+\lambda_1^- - y)(1-\frac{y}{1+\lambda_1^-})}{2[1+(1-y)^2]}\left(\frac{y-\frac{\lambda_1^-}{2}}{y-\lambda_1^-}\right)\frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})\cdot\left(\mathbf{l}_\perp - \frac{y}{1+\lambda_1^-}\mathbf{k}_{1\perp}\right) + \frac{\left(\frac{y}{1+\lambda_1^-}\right)^2(y-\lambda_1^-)^2}{1+(1+\lambda_1^- - y)(1-\frac{y}{1+\lambda_1^-})}M^2}{\left[\left(\mathbf{l}_\perp - \frac{y}{1+\lambda_1^-}\mathbf{k}_{1\perp}\right)^2 + (\frac{y}{1+\lambda_1^-})^2M^2\right][(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2M^2]}\left.\right] + \ldots\ldots\left.\right\}$$

Medium-induced gluon emission spectrum is directly controlled by differential scattering rate (or generalized $\hat{q}$)

$$\mathcal{D}(k_1^-, \mathbf{k}_{1\perp}) = (2\pi)^3\frac{dP_{\text{el}}}{dk_1^- d^2\mathbf{k}_{1\perp}dZ_1^-}$$

Medium-induced gluon emission beyond collinear expansion & soft gluon emission limit with transverse & longitudinal scatterings for massive/massless quarks

Only transverse scatterings

- Modeling the traversed nuclear medium by heavy static scattering centers (only transverse scatterings)

$$\frac{dN_g^{\rm med}}{dyd^2\mathbf{l}_\perp} = \frac{\alpha_s}{2\pi^2}P(y)\int dZ_1^- \int d^2\mathbf{k}_{1\perp}\frac{dP_{\rm el}}{d^2\mathbf{k}_{1\perp}dZ_1^-}$$

$$\times\left\{C_A\left[2-2\cos\left(\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2}{l_\perp^2+y^2M^2}\frac{Z_1^-}{\tilde{\tau}^-_{\rm form}}\right)\right]\times\left[\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+\frac{y^4}{1+(1-y)^2}M^2}{\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2\right]^2}\right.\right.$$

$$-\frac{1}{2}\frac{\mathbf{l}_\perp\cdot(\mathbf{l}_\perp-\mathbf{k}_{1\perp})+\frac{y^4}{1+(1-y)^2}M^2}{[l_\perp^2+y^2M^2]\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2\right]}-\frac{1}{2}\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})\cdot(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})+\frac{y^4}{1+(1-y)^2}M^2}{\left[(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2+y^2M^2\right]\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2\right]}\left.\vphantom{\frac{1}{2}}\right]$$

$$+\left(\frac{C_A}{2}-C_F\right)\left[2-2\cos\left(\frac{Z_1^-}{\tilde{\tau}^-_{\rm form}}\right)\right]\left[\frac{\mathbf{l}_\perp\cdot(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})+\frac{y^4}{1+(1-y)^2}M^2}{[l_\perp^2+y^2M^2]\left[(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2+y^2M^2\right]}-\frac{l_\perp^2+\frac{y^4}{1+(1-y)^2}M^2}{[l_\perp^2+y^2M^2]^2}\right]$$

$$\left.+C_F\left[\frac{(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2+\frac{y^4}{1+(1-y)^2}M^2}{\left[(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2+y^2M^2\right]^2}-\frac{l_\perp^2+\frac{y^4}{1+(1-y)^2}M^2}{[l_\perp^2+y^2M^2]^2}\right]\right\}.$$

Soft gluon emission approximation

- Further taking soft gluon emission approximation: $y^2 M \ll yM \sim l_\perp \sim k_{1\perp}$

$$\frac{dN_g^{\rm med}}{dy d^2 \mathbf{l}_\perp} = \frac{\alpha_s}{2\pi^2} P(y) \int dZ_1^- \int d^2\mathbf{k}_{1\perp} \frac{dP_{\rm el}}{d^2\mathbf{k}_{1\perp} dZ_1^-} \times C_A \left[2 - 2\cos\left(\frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + y^2M^2}{l_\perp^2 + y^2M^2} \frac{Z_1^-}{\tilde{\tau}_{\rm form}^-} \right) \right]$$
$$\times \left[\frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2}{\left[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + y^2M^2 \right]^2} - \frac{\mathbf{l}_\perp \cdot (\mathbf{l}_\perp - \mathbf{k}_{1\perp})}{[l_\perp^2 + y^2M^2] \left[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + y^2M^2 \right]} \right].$$

- This agrees with the DGLV first-order-in-opacity formula.

- Jet transport parameter is related to the differential elastic scattering rate as follows:

$$\hat{q}_{lc} = \frac{d\langle k_{1\perp}^2 \rangle}{dL^-} = \int \frac{dk_1^- d^2\mathbf{k}_{1\perp}}{(2\pi)^3} \mathbf{k}_{1\perp}^2 \mathcal{D}(k_1^-, \mathbf{k}_{1\perp}) = \int \frac{d^2\mathbf{k}_{1\perp}}{(2\pi)^2} \mathbf{k}_{1\perp}^2 \mathcal{D}_\perp(\mathbf{k}_{1\perp}) = \int d^2\mathbf{k}_{1\perp} \mathbf{k}_{1\perp}^2 \rho^- \frac{d\sigma_{\rm el}}{d^2\mathbf{k}_{1\perp}}.$$

Implementation of inelastic radiation in LBT

- **Average number of radiated gluons in Δt:**

$$\langle N_g\rangle(E,T,t,\Delta t) = \Gamma_g \Delta t = \Delta t \int dx\, dk_\perp^2 \frac{dN_g}{dx\, dk_\perp^2 dt}$$

- **Poisson distribution for the number *n* of radiated gluons during Δt:**

$$P(n) = \frac{\langle N_g\rangle^n}{n!} e^{-\langle N_g\rangle}$$

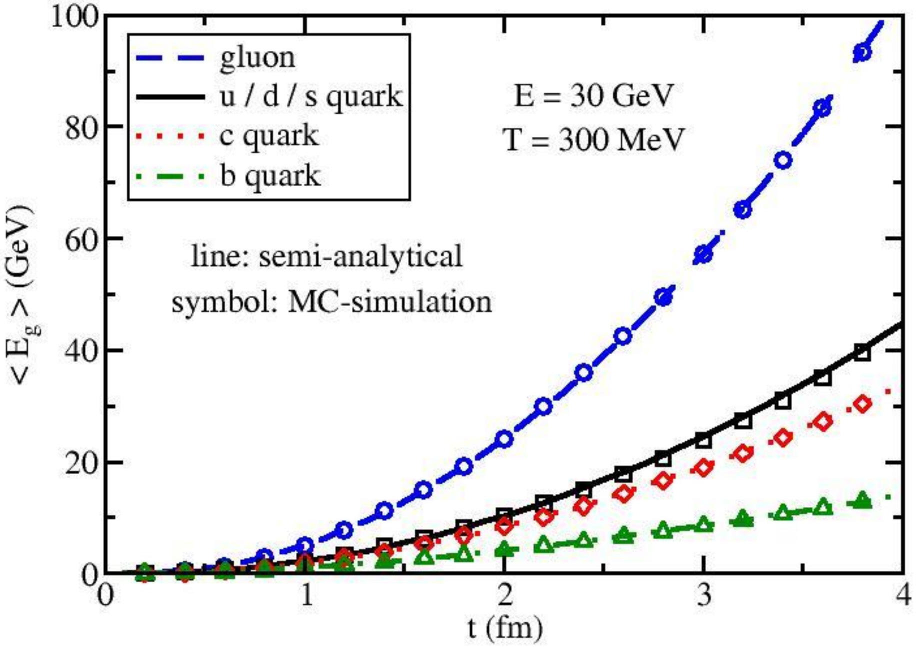
- **Probability of inelastic interaction during Δt:**

$$P_{inel} = 1 - e^{-\langle N_g\rangle}$$

- **Zhu, Wang, PRL 2013; He, Luo, Wang, Zhu, PRC 2015; Cao, Tan, GYQ, Wang, Phys.Rev.C 94 (2016) 1, 014909; Phys.Lett.B 777 (2018) 255-259**

Model implementation of inelastic radiation

- **Calculate $\langle N_g \rangle$ and P_{inel}**
- **If gluon radiation happens, sample *n* gluons from Poisson distribution**
- **Sample *E&p* of radiatied gluons using the differential radiation spectrum**
- **First do $2 \to 2$ process, then adjust *E&p* of $2+n$ final partons to guarantee *E&p* conservation for $2 \to 2+n$ process**



$\langle E_g \rangle$ from our MC simulation agrees with the semi-analytical result.

Combine elastic & inelastic

- **Total probability:**

$$P_{tot} = 1 - e^{-\Gamma_{tot}\Delta t} = P_{el} + P_{inel} - P_{el}P_{inel}$$

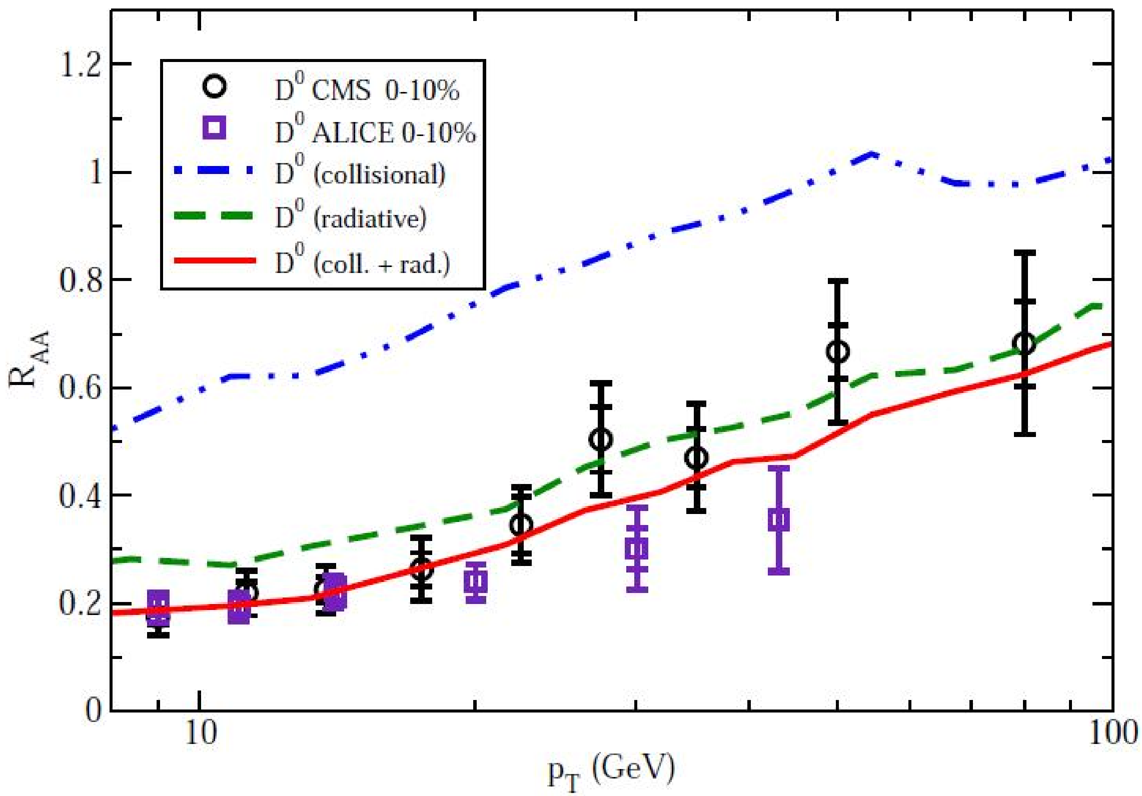
  - **Pure elastic scattering without gluon radiation: $P_{el}(1 - P_{inel})$**
  - **Inelastic scattering: P_{inel}**

- **Use P_{tot} to determine whether jet parton interact with thermal medium**

- **If jet-medium interaction happens, then determine whether it is pure elastic or inelastic**

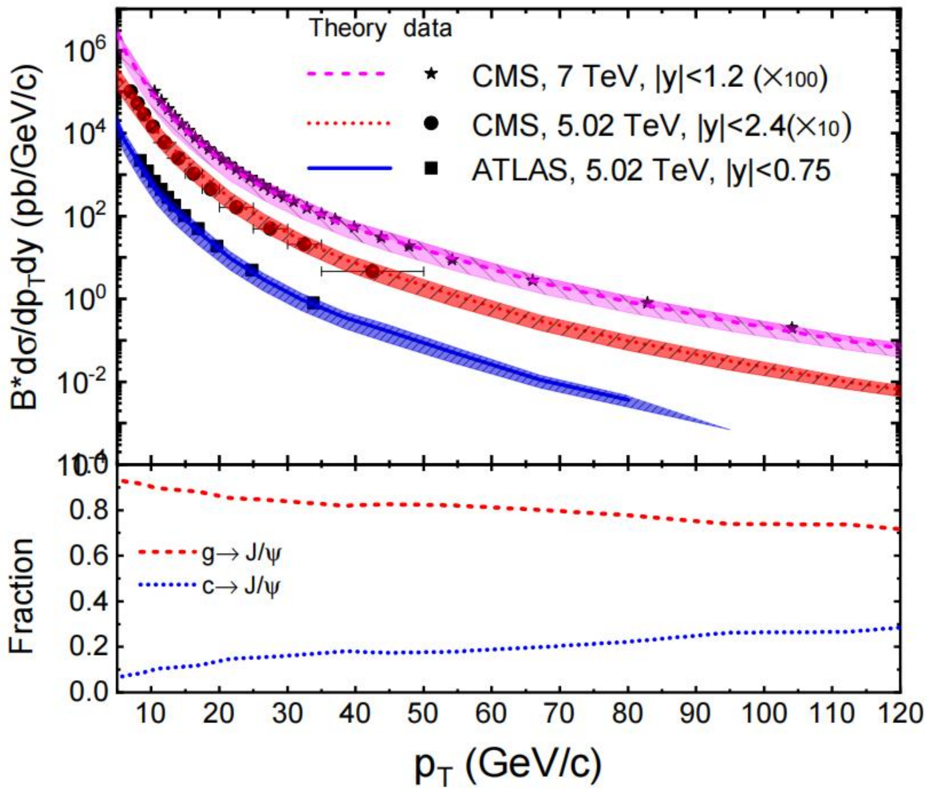
- **Then simulate $2 \rightarrow 2$ or $2 \rightarrow 2 + n$ process**

Radiative and collisional contributions



Radiative E loss provides more dominant contributions to R_{AA}, collisional E loss also has sizable contributions to R_{AA} at not-very-high p_T regime and diminishes with increasing p_T.

Gluons dominate high p_T J/Ψ production



Leading power (p_T^2/m_c^2) NRQCD:

$$d\sigma[AB \to J/\psi + X] = \sum_i d\hat{\sigma}_{AB\to i+X} \otimes D_{i\to J/\psi}$$

$$D_{i\to J/\psi}(z,\mu) = \sum_n \hat{d}_{i\to[Q\bar{Q}(n)]}(z,\mu)\langle \mathcal{O}^{J/\psi}_{[Q\bar{Q}(n)]}\rangle$$

Gluon fragmentation-improved PYTHIA (GFIP)

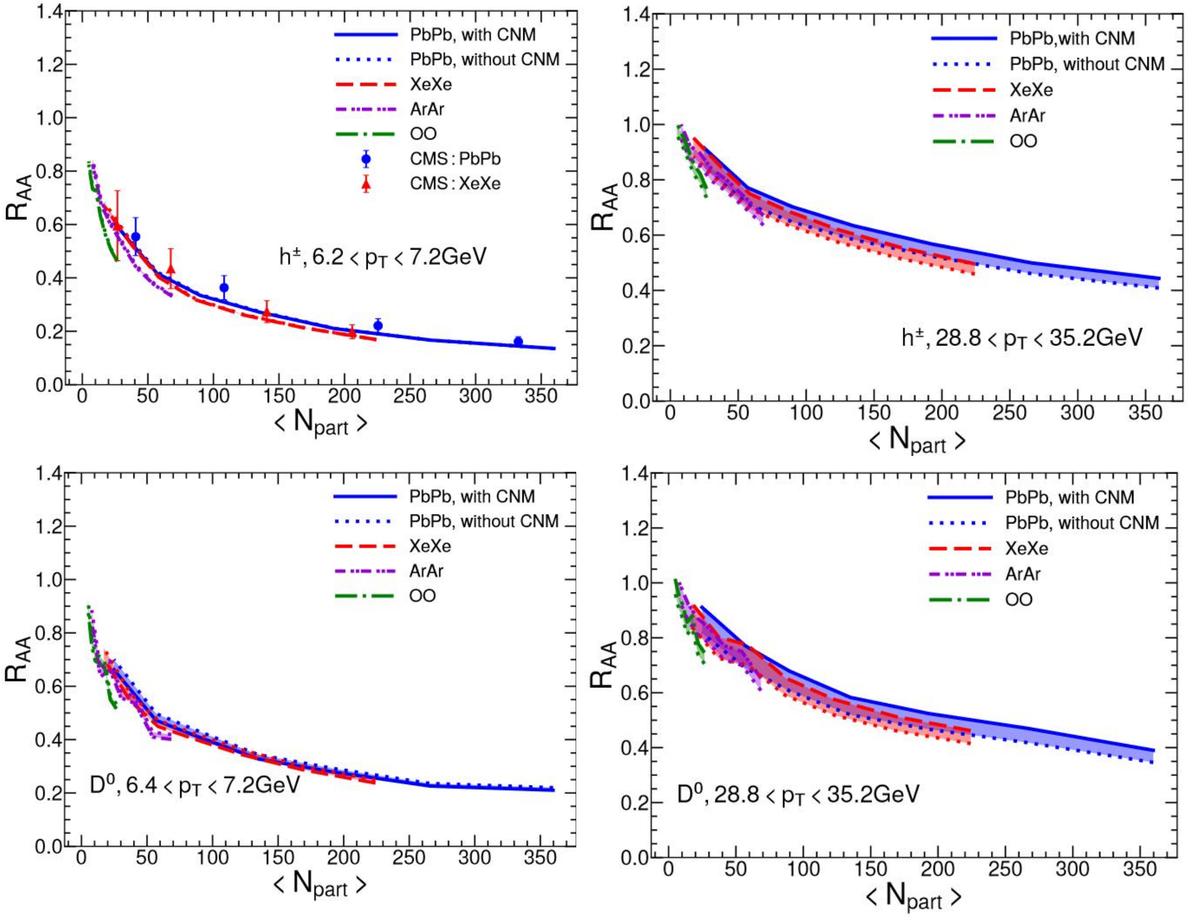
MadGraph for hard parton creation
PYTHIA8 for parton shower
Short-distance coefficients from 1311.7078, 1208.5301
Long-distance matrix element from 1403.3612.

Within the framework of leading power NRQCD, gluons dominate high p_T J/Ψ production.

S.-L. Zhang, J. Liao, GYQ, E. Wang, H. Xing, 2208.08323

Ma, Qiu, Zhang, PRD, 2014; Bodwin, Kim, Lee, JHEP 2012; Bodwin, Chung, Kim, Lee, PRL 2014

When does jet quenching disappear?



R_{AA} have good scaling behaviors with respect to systems size.

Prediction of sizable jet quenching in OO collisions.

R_{pA} ~ 1 in pA is mainly due to small system size

Xing, Cao, GYQ, Xing, PLB 2020; Liu, Xing, Wu, GYQ, Cao, Xing, PRC 2022

Full jet evolution in medium

- **Solve the 3D (energy & transverse momentum) evolution for shower partons inside the full jet**
- **Include both collisional (the longitudinal drag and transverse diffusion) and all radiative/splitting processes**

$$\frac{d}{dt} f_j(\omega_j, k_{j\perp}^2, t) = \left(\hat{e}_j \frac{\partial}{\partial \omega_j} + \frac{1}{4} \hat{q}_j \nabla_{k_\perp}^2 \right) f_j(\omega_j, k_{j\perp}^2, t)$$

Drag & transverse broadening

$$+ \sum_i \int d\omega_i dk_{i\perp}^2 \frac{d\tilde{\Gamma}_{i\to j}(\omega_j, k_{j\perp}^2 | \omega_i, k_{i\perp}^2)}{d\omega_j d^2 k_{j\perp} dt} f_i(\omega_i, k_{i\perp}^2, t)$$

Gain terms

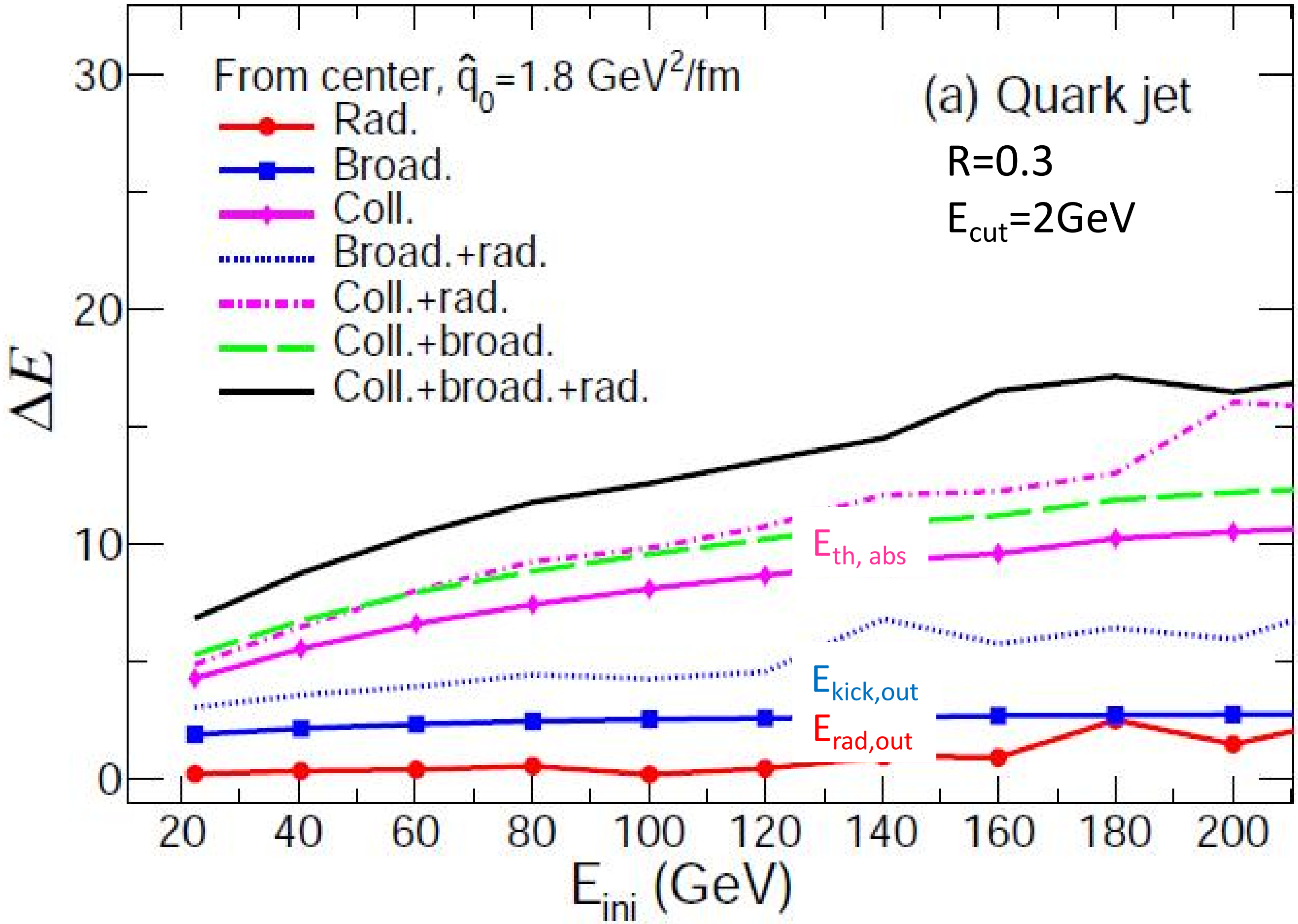
$$- \sum_i \int d\omega_i dk_{i\perp}^2 \frac{d\tilde{\Gamma}_{j\to i}(\omega_i, k_{i\perp}^2 | \omega_j, k_{j\perp}^2)}{d\omega_i d^2 k_{i\perp} dt} f_j(\omega_j, k_{j\perp}^2, t)$$

Loss terms

$$E_{jet}(R) = \sum_i \int_R \omega_i f_i(\omega_i, k_{i\perp}^2) d\omega_i dk_{i\perp}^2$$

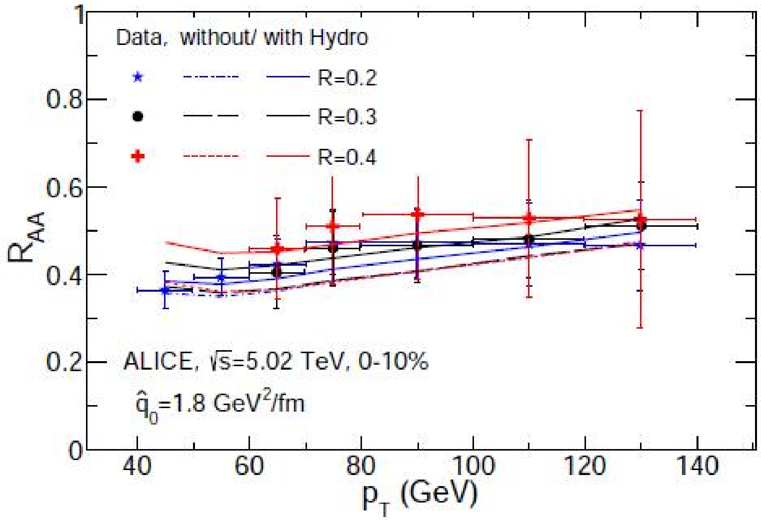
Chang, GYQ, PRC 2016

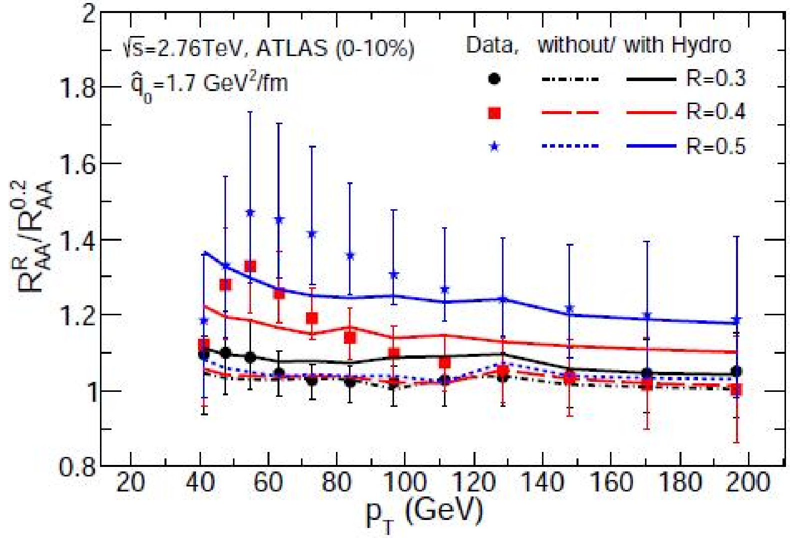
Full jet energy loss (radiative, collisional, broadening)

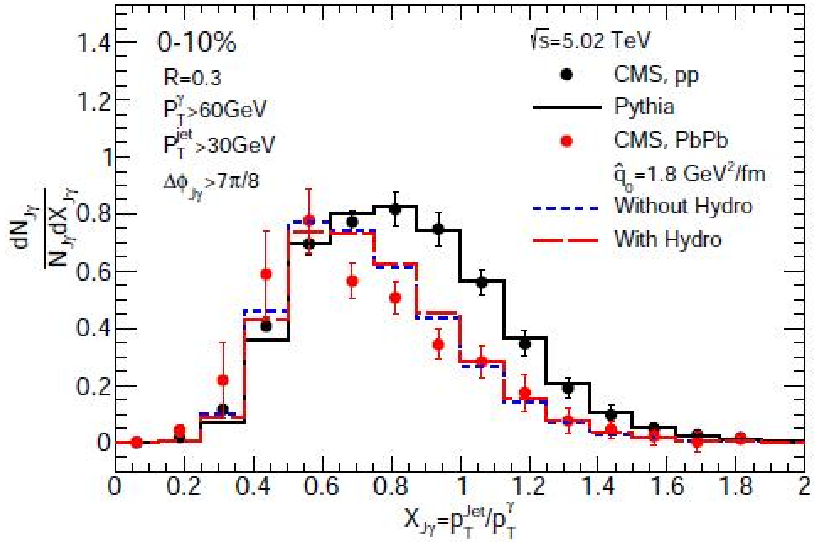


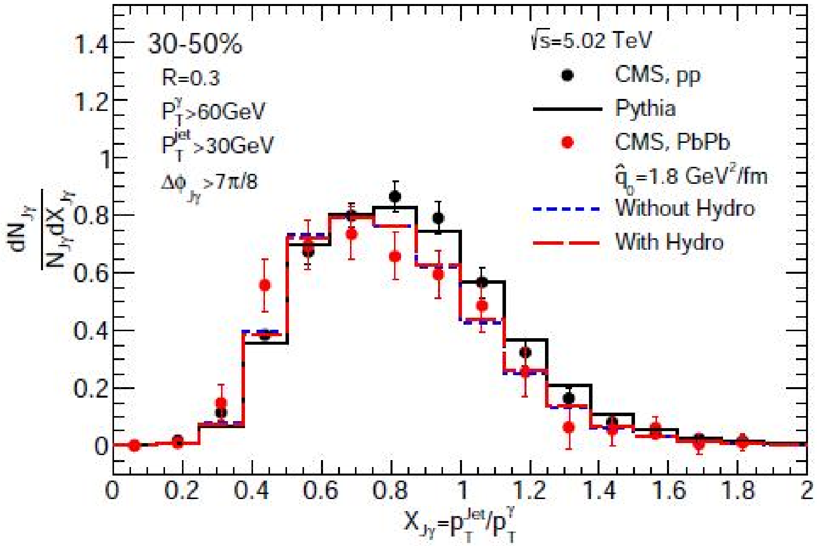
Chang, GYQ, PRC 2016

Jet R_{AA} and photon-jet asymmetry









Chang, Tachibana, GYQ, PLB 2020

Generalized k_T family of jet reconstruction algorithms

- (1) Consider all particles in the list, and compute all distances d_{iB} and d_{ij}
- (2) For particle i, find min(d_{ij}, d_{iB})
- (3) If min(d_{iB}, d_{ij}) = d_{iB}, declare particle i to be a jet, and remove it from the list of particles. Then return to (1)
- (4) If min(d_{iB}, d_{ij})=d_{ij}, recombine i & j into a single new particle. Then return to (1)
- (5) Stop when no particles are left

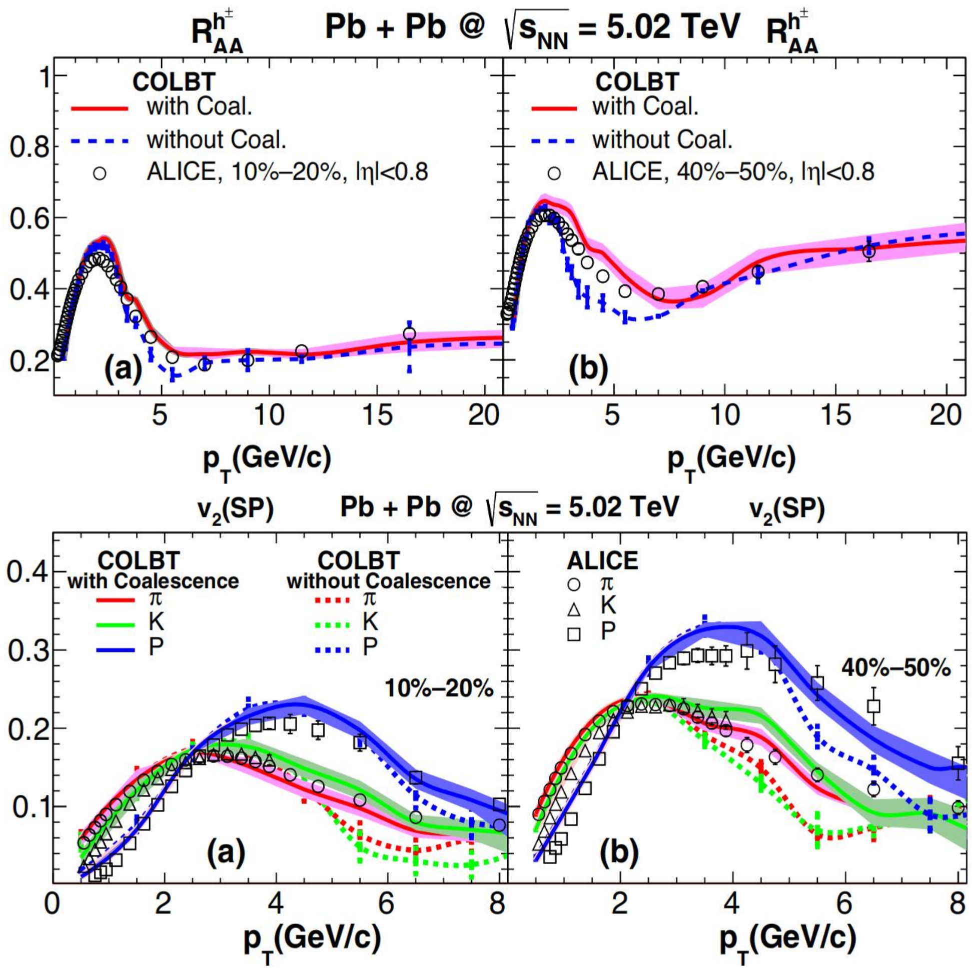
$$d_{iB} = p_{T,i}^{2p}$$

$$d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2}$$

$$\Delta R_{ij}^2 = (\phi_i - \phi_j)^2 + (\eta_i - \eta_j)^2$$

p=1: k_T algorithm
p=0: Cambridge/Aachen algorithm
p=-1: anti-k_T algorithm

Solve R_{AA} & v_2 puzzle



It is a long-standing challenge to have a consistent description of R_{AA} and v_2 at all p_T, especially at intermediate p_T.

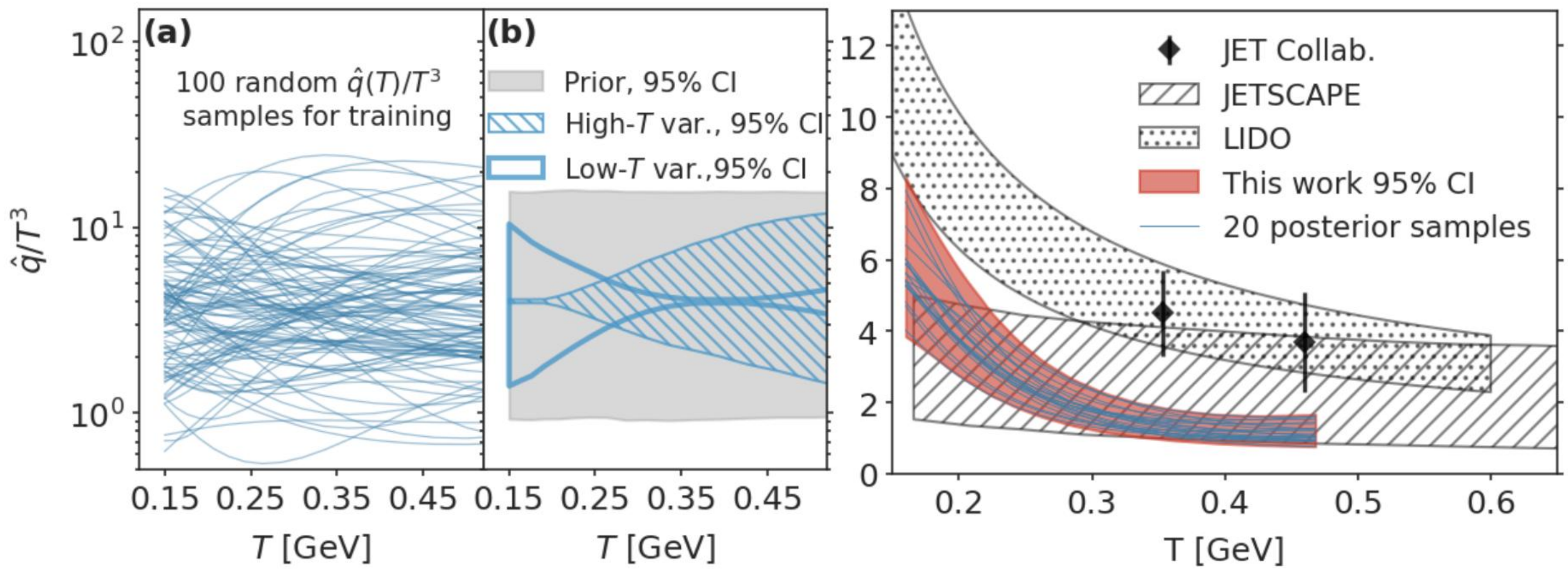
By coupling CoLBT-hydro model [1] and the hybrid hydro+frag+coal hadronization model [2], R_{AA} & v2 puzzle is solved [3].

R_{AA}, v_2 and their flavor dependence can be well described in this coupled framework.

Quark coalescence (& hadron cascade) is important to explain R_{AA} and v_2 at intermediate p_T.

[1] W. Chen, S. Cao, T. Luo, L.G. Pang, X.N. Wang, Phys. Lett. B 777, 86-90 (2018)
[2] W. Zhao, C.M. Ko, Y.X. Liu, GYQ, H. Song, Phys. Rev. Lett. 125, 072301 (2020)
[3] W. Zhao, W. Ke, W. Chen, T. Luo, X.N. Wang, Phys. Rev. Lett. 128, 022302 (2022)

Extract jet transport coefficient $\hat{q}$



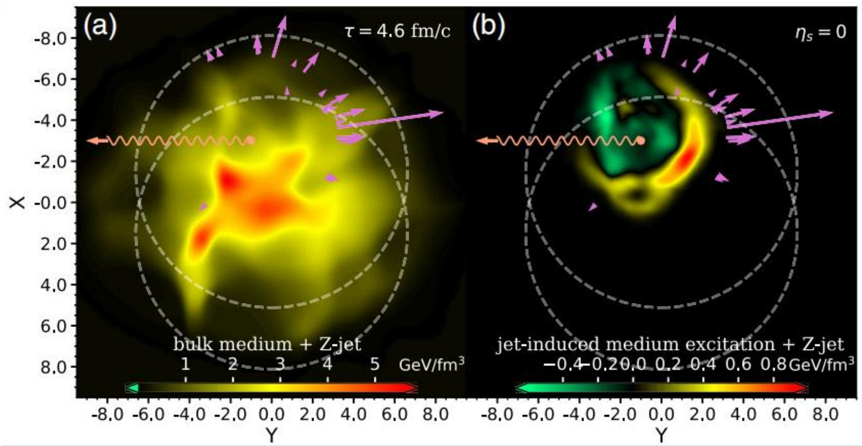
Bayesian analyses often rely on explicit parametrizations of unknown function, which introduces long-range correlations in regions of the variable space.

Develop information field approach to Bayesian Inference: the prior distribution of the unknown function is free of long-range correlations.

The extracted $\hat{q}/T^3$ exhibits a strong T-dependence (no bias by a specific form).

M. Xie, W. Ke, H. Zhang, X. N. Wang, arXiv:2206.01340.

Diffusion wake: 2D structure

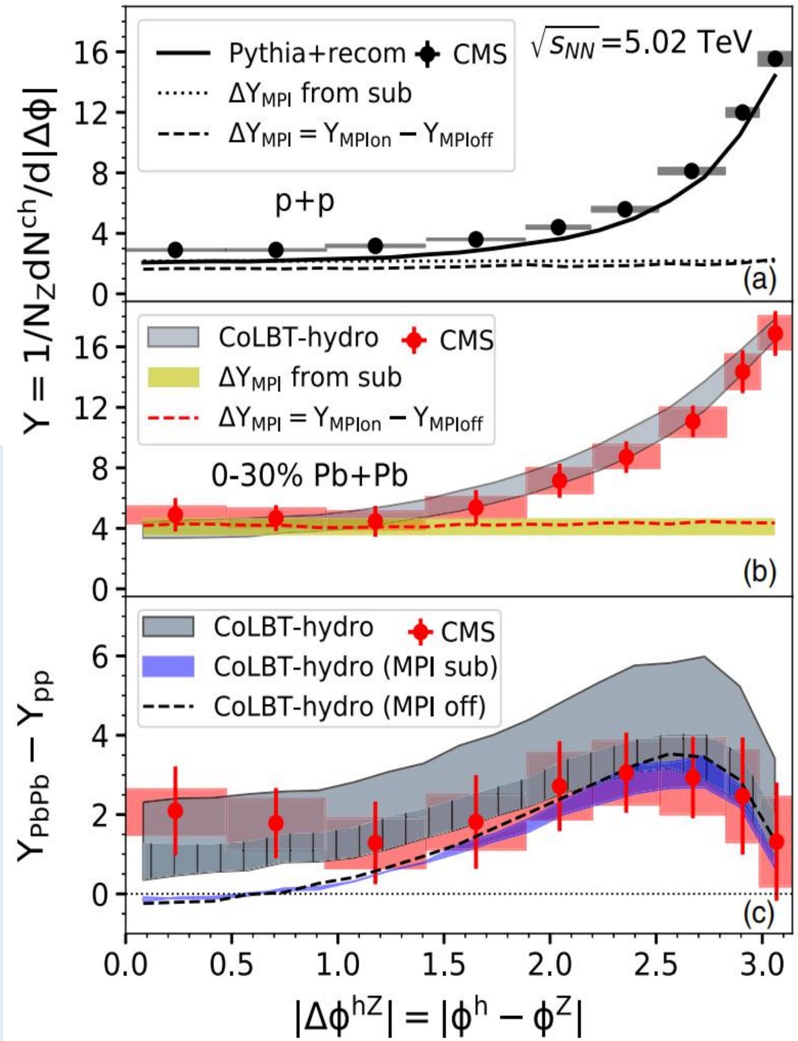


While the wave front enhances soft hadron yield on near side, the diffusion wake leads to depletion of soft hadrons in opposite side.

CMS data show an enhancement of soft hadrons in both Z and jet directions.

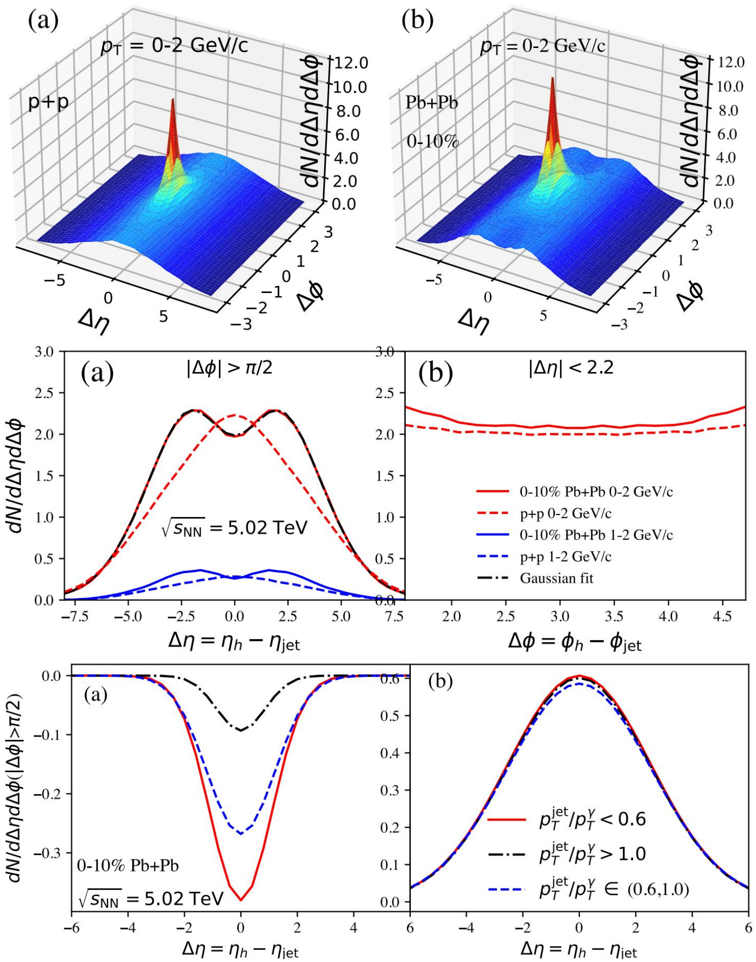
Hadrons in Z (opposite to jet) direction mainly come from MPI effect. After subtracting MPI with a mixed event procedure, the signal of diffusion wake become visible.

Use transverse & longitudinal jet tomography to enhance the diffusion wake signal.



W. Chen, S. Cao, T. Luo, L.G. Pang, X. N. Wang, Phys. Lett. B 777, 86-90 (2018); Z. Yang, W. Chen, Y. He, W. Ke, L. Pang, X. N. Wang, Phys. Rev. Lett. 127, 082301 (2021)

Diffusion wake: 3D structure



Signal: the double-peak structure in the γ-hadron correlations as a function of rapidity and azimuthal angle.

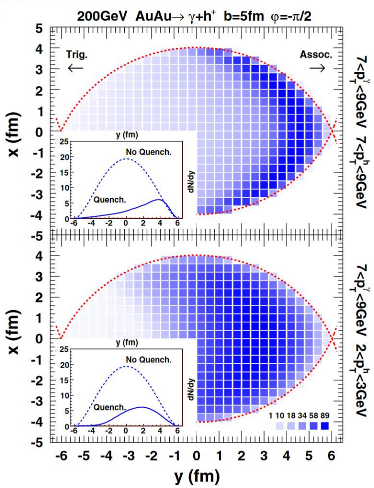
Such double-peak structure is a combined effect of a valley structure caused by the diffusion wake and a ridge from MPI effect.

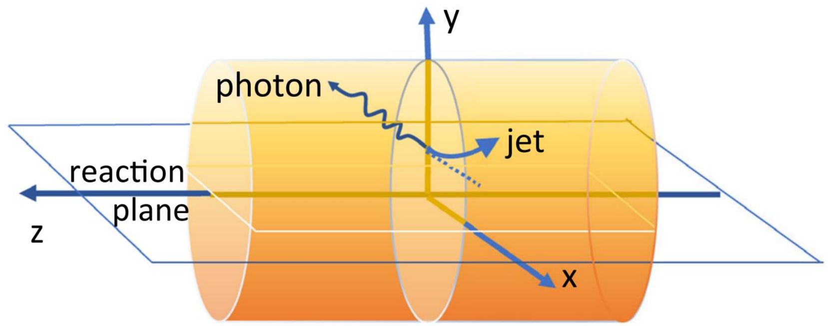
The depth of the diffusion wake valley increases with increasing jet energy loss as characterized by γ-jet asymmetry.

Future data on the diffusion wake together with other observables will provide combined constraints on the EoS and transport properties of QGP.

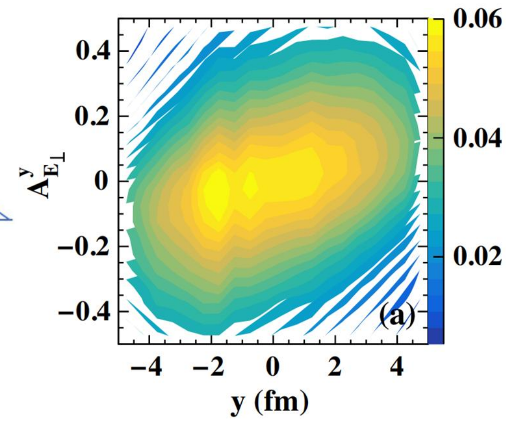
Z. Yang, T. Luo, W. Chen, L.G. Pang , X. N. Wang, Phys. Rev. Lett. 130, 052301 (2023)

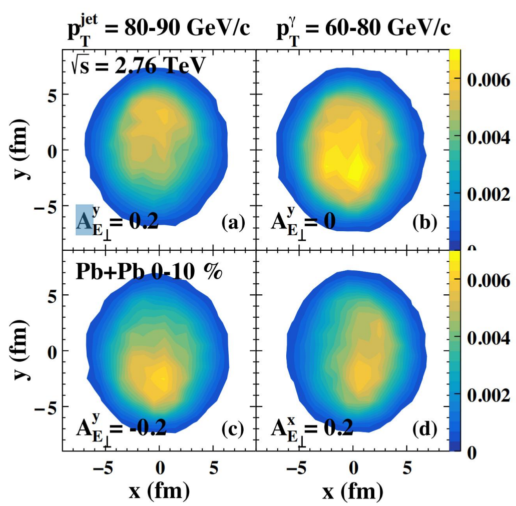
Transverse (& longitudinal) jet tomography





$$A_N^{\vec{n}} = \frac{\int d^3r d^3k f_a(\vec{k},\vec{r}) \mathrm{Sign}(\vec{k}\cdot\vec{n})}{\int d^3r d^3k f_a(\vec{k},\vec{r})}.$$





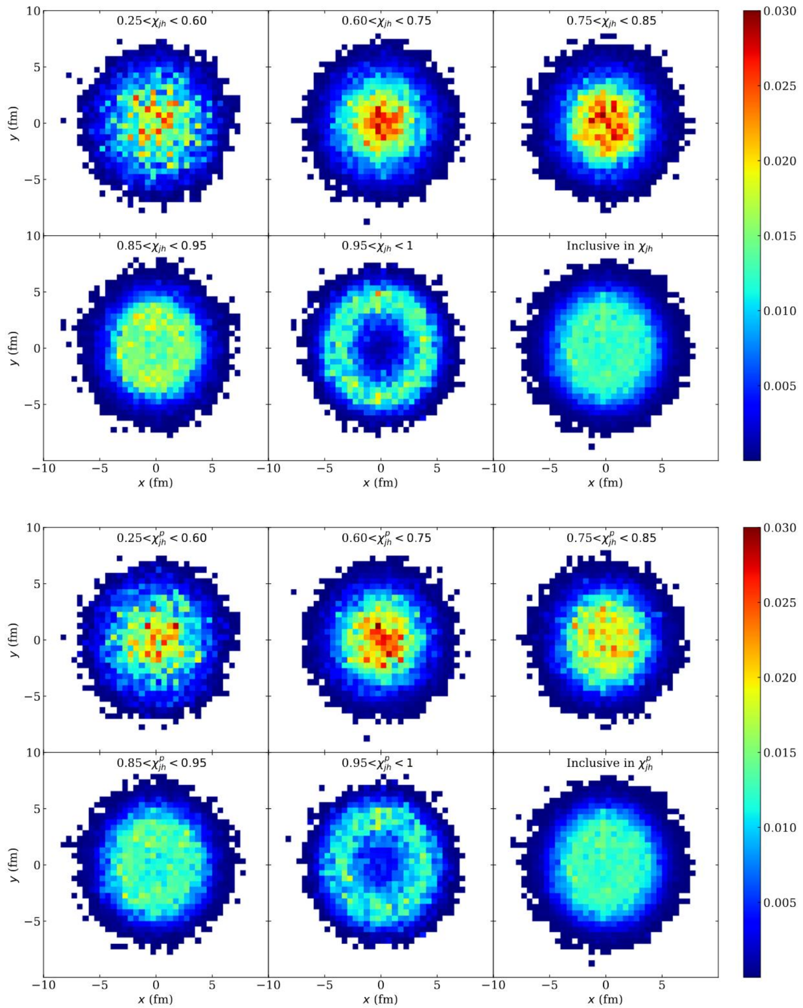
The gradient of $\hat{q}$ transverse to the jet direction can lead to the asymmetry of particle production with respect to the jet-beam plane.

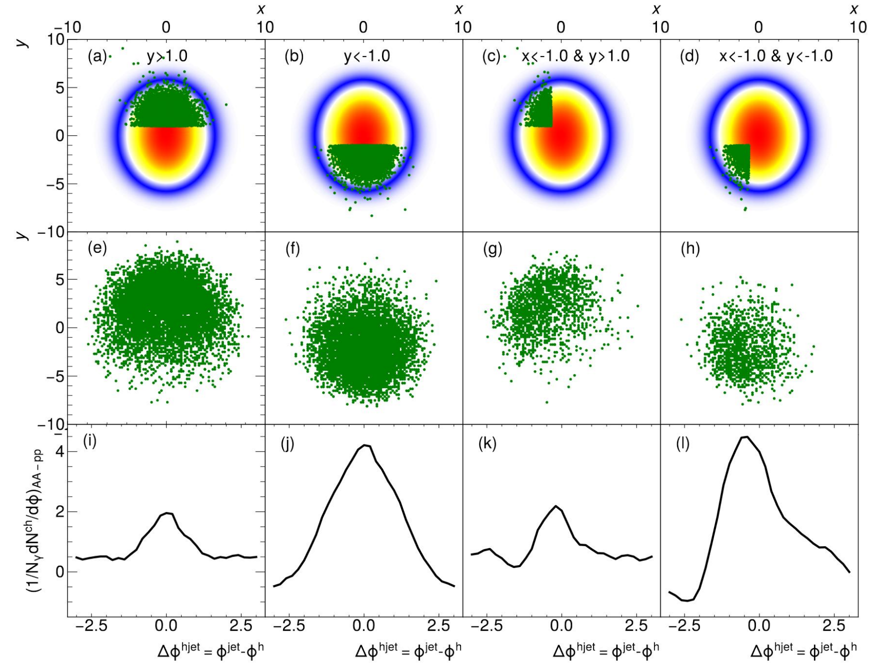
One can use this transverse asymmetry to localize the initial jet position [1], which is termed gradient (transverse) jet tomography.

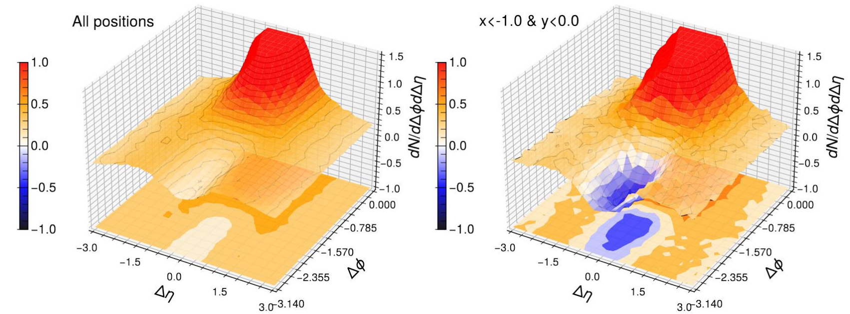
By combining the longitudinal jet tomography [2], the study of jet quenching along a specific path becomes possible.

[1] Y. He, L. G. Pang, X. N. Wang, Phys. Rev. Lett. 125, 122301 (2020)
[2] H. Z. Zhang, J. F. Owens, E. Wang, X. N. Wang, Phys. Rev. Lett. 103, 032302 (2009)

Machine learning jet tomography







Y. L. Du, D. Pablos, K. Tywoniuk, Phys.Rev.Lett. 128 (2022) 1, 012301; JHEP 03 (2021) 206.
Z. Yang, W. Chen, Y. He, W. Ke, L. Pang, X. N. Wang, arXiv:2206.02393.